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TEARDOWN AND INSPECTION OF THE CUMMINS VTA-903 - EVALUATED USING THE SINGLE COMMON POWERTRAIN LUBRICANT (SCPL)

INTERIM REPORT
TFLRF No. 450

by
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U.S. Army TARDEC Fuels and Lubricants Research Facility
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U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD21 – Task 2.6)

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EXECUTIVE SUMMARY

The U.S. Army TARDEC Fuels & Lubricants Technology Team has developed a Single Common Powertrain Lubricant (SCPL), designed to consolidate multiple military lubricant specifications into a single product, or single specification. The application of the SCPL includes engine lubrication, power shift transmission operation, and limited use in hydraulic systems. It is designed to operate in ambient temperatures ranging from low temperature arctic to high temperature desert conditions, reduce the logistics burden of the U.S. Army materiel supply chain through product simplification, and provide increased performance and improved vehicle efficiency over currently specified petroleum, oil, lubricant (POL) products.

After its initial development in high fleet density military engine applications such as the General Engine Products (GEP) family of engines used in the High Mobility Multipurpose Wheeled Vehicle (HMMWV), and the Caterpillar (CAT) C7 used in many medium tactical vehicles, the SCPL was tested in other lower fleet density engines to confirm performance over the wide range of vehicles that make up the military fleet. These include more common engine platforms of key equipment groups in the fleet, as well as specific platforms that are unique or have shown high lubricant sensitivity in the past. As a result, the SCPL was recently evaluated by TARDEC in the Cummins VTA-903, as used in the M3A3 Bradley Fighting Vehicle, a mainstay of the Army's combat fleet. The VTA-903 is a 14.8 liter, V8, turbocharged after-cooled diesel engine, producing approximately 600 horsepower and 1225 lb-ft of torque. The engine was tested using the SCPL and following procedures outlined in the 400 hour NATO hardware endurance test cycle. After dyno testing was completed, the engine was shipped to the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio, TX for a full tear down and internal inspection.

Upon teardown at TFLRF, the engine was found to be in acceptable overall condition. Detailed inspection, metrology, and component ratings were completed to document and quantify the engines condition. The visual inspection of all removed components showed no areas of concern. All major engine subassemblies removed were found to be in acceptable working order, and condition consistent with a used healthy engine. The candidate SCPL evaluated showed

acceptable overall deposit control. Piston deposit ratings were found to be comparable to those seen during the SCPL development using the GEP 6.5L(T). In addition, none of the ring packs showed ring face distress, deposit buildup, or ring sticking. Post test engine measurements verified that all components apart from four second ring end gaps were found to comply with the recommended ranges for engine rebuilding. This suggest acceptable performance and wear protection of the SCPL tested. The four ring end gaps out of specification were found to be a minor non-conformance, and did not raise a real concern of the performance of the SCPL tested. It is the opinion of TFLRF staff that all results gathered from the Cummins VTA-903 teardown support the use of the tested SCPL in this family of engines.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period September 2012 through December 2013 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Mr. Allen Comfort of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by Dianna Barrera.

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society of Testing & Materials
AT	Anti-Thrust
AVG	Average
BFV	Bradley Fighting Vehicle
CAT	Caterpillar
EOT	End Of Test
GEP	General Engine Products
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HP	Horsepower
ID	Inside Diameter
lb-ft	Pound Feet
MIL-PRF	Military Performance Specification
NATO	North Atlantic Treaty Organization
POL	Petroleum, Oil, Lubricants
QTR	Quarter
SCPL	Single Common Powertrain Lubricant
SwRI	Southwest Research Institute
T	Thrust
TARDEC	Tank Automotive Research Development & Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
TM	Technical Manual
US	United States
VTA	Vee, Turbocharged, Aftercooled
WD	Work Directive

1.0 BACKGROUND

The U.S. Army TARDEC Fuels & Lubricants Technology Team has developed a Single Common Powertrain Lubricant (SCPL), designed to consolidate multiple military lubricant specifications into a single product, or single specification. The application of the SCPL includes engine lubrication, power shift transmission operation, and limited use in hydraulic systems where MIL-PRF-2104 and MIL-PRF-46167 products are currently used. The SCPL is designed to operate in ambient temperatures ranging from low temperature arctic to high temperature desert conditions, representative of the wide range of potential military operating conditions seen worldwide. The development of the SCPL allows for a single lubricant specification to be universally used in tactical and combat vehicles, despite their seasonal or geographical location, while additionally reducing the logistics burden of the Army's supply chain by requiring only one lubricant product to be procured and distributed to its worldwide operations. In addition, technological lubricant advancements of the SCPL allow for improved oil performance and vehicle efficiency over current military specified lubricants [1,2]. All of these areas provide a cost benefit to military operations.

This report covers the tear down and inspection of a Cummins VTA-903 engine, after being evaluated using an SCPL candidate generated under TARDEC-SwRI Work Directives (0042) 0001, 0017, and 0021. The Cummins VTA-903, as used in the M3A3 Bradley Fighting Vehicle (BFV), is a 14.8 liter, V8, turbocharged after-cooled diesel engine, producing approximately 600 hp, and 1225 lb-ft of torque at their respective peaks. This engine was dyno tested at the U.S. Army TARDEC in Warren, MI, with testing administered by the Ground Vehicle Power & Mobility team. It was evaluated following the procedures outlined in the 400 hour NATO hardware endurance cycle under desert type operating conditions (120ºF ambient, 175ºF JP-8 fuel inlet), and successfully operated the full 400 hour test duration without experiencing any major hardware or lubricant failure. After completing the engine durability test, the engine was crated and shipped to the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio, TX, for a full tear down and internal inspection. Findings of the inspection are covered as follows:

2.0 OBJECTIVE & APPROACH

The objective of this project was to complete a tear down and inspection of a Cummins VTA-903 diesel engine, which was evaluated using a candidate TARDEC developed Single Common Powertrain Lubricant (SCPL). The tear down and inspection process was designed to assess the internal condition of the engine components, in an effort to provide a semi-quantitative measure of internal engine wear and deposit formation incurred during engine dynamometer testing, and assess the overall performance of the SCPL candidate in this family of engines. After completing the initial engine teardown, the TARDEC Fuels and Lubricants Research Facility (TFLRF) completed the following internal engine measurements (metrology) to quantify engine wear. Post test measurements were then compared to typical pre-test tolerance ranges to determine indicated performance (note: no pre-test engine measurements were made available at the time of inspection):

- Cylinder Bore Diameter
- Piston Skirt Diameter (calculated bore to skirt clearance)
- Piston Ring End gaps
- Piston Ring to Groove Clearance
- Piston Pin Diameter
- Piston Pin Bore Diameter (calculated pin to bore clearance)
- Connection Rod Pin Bore Diameter (calculated pin to bore clearance)
- Main and Connecting Rod Bearing Clearance

In addition to the listed metrology, TFLRF also completed extensive ratings of internal components to assess the SCPL candidates ability to control engine deposit formation, and provide a semi-quantitative measure of overall engine deposit levels. All ratings were completed following the procedures outlined in the ASTM Deposits and Distress Rating Manual 20 [3], and included:

- Piston Ring Sticking
- Piston Scuffing
- Piston Carbon Demerits
- Piston Lacquer Demerits
- Top and Intermediate Ring Groove Fill
- Top Land Heavy and Flaked Carbon
- Valve Tulip Merits

After all metrology and ratings tasks were completed, key engine parts were then photographed to provide visual documentation of the internal condition of the engine.

In addition to these specific tasks aimed at documenting the engines condition, several other inspection tasks were completed in an aim to answer specific questions that arose during the dyno testing portion of the project. These included investigation into the engine's lubrication pressure system to diagnose the cause of unusual oil pressure and flow measurements during dyno testing, as well as an investigation into the engines rear main crankshaft seal to determine the cause of an oil leak experienced during testing. All of these areas are covered in detail in the remainder of this report.

3.0 ENGINE UNCRATING

The SCPL evaluated engine was received by TFLRF in a standard government issue engine shipping container specific to the Cummins 903 engine family. It was received at the TFLRF in the 1st QTR FY13, and remained in storage as received until late April 2013 when the funding for this effort was received and the inspection process was initiated. During this approximate 6 month storage time, the engine container was stored in a partially enclosed (3 sided) storage building. The shipping crate was not exposed to direct weather during this time. Upon opening at the start of inspection, a significant amount of moisture was noted within the container. In addition, excess used oil had accumulated in the bottom of the container which required cleaning prior to removal. The moisture present within the container was unexpected, and may have contributed to, or become apparent in some results reported within this report. Specific notations will be made in each suspected area. Figure 1 and Figure 2 show generic shots of the engine as received and uncrated at TFLRF. Figure 3 and Figure 4 show the moisture and oil present within the container upon opening.

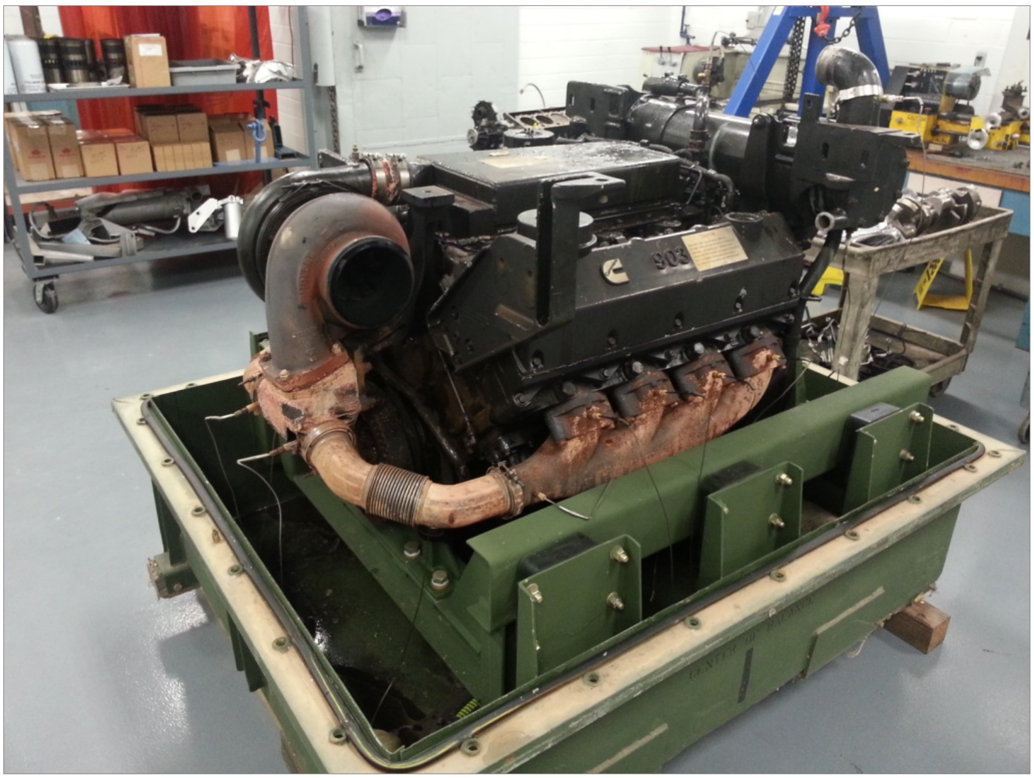

Figure 1. Cummins VTA-903, Container Photo 1

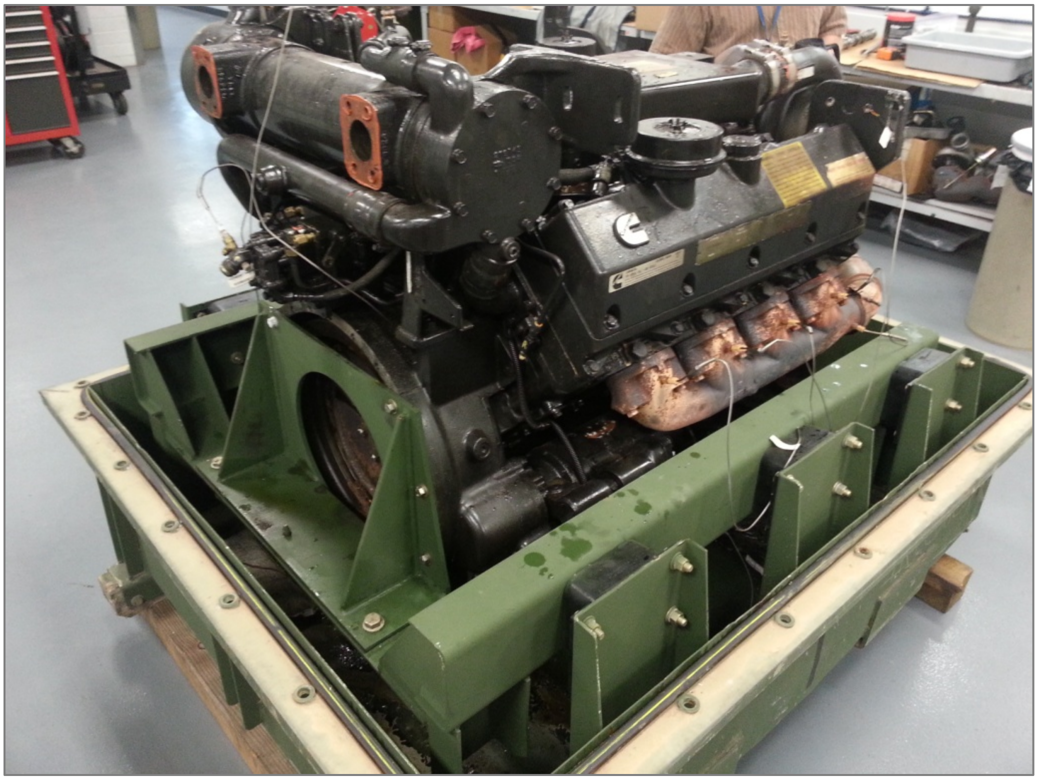

Figure 2. Cummins VTA-903, Container Photo 2

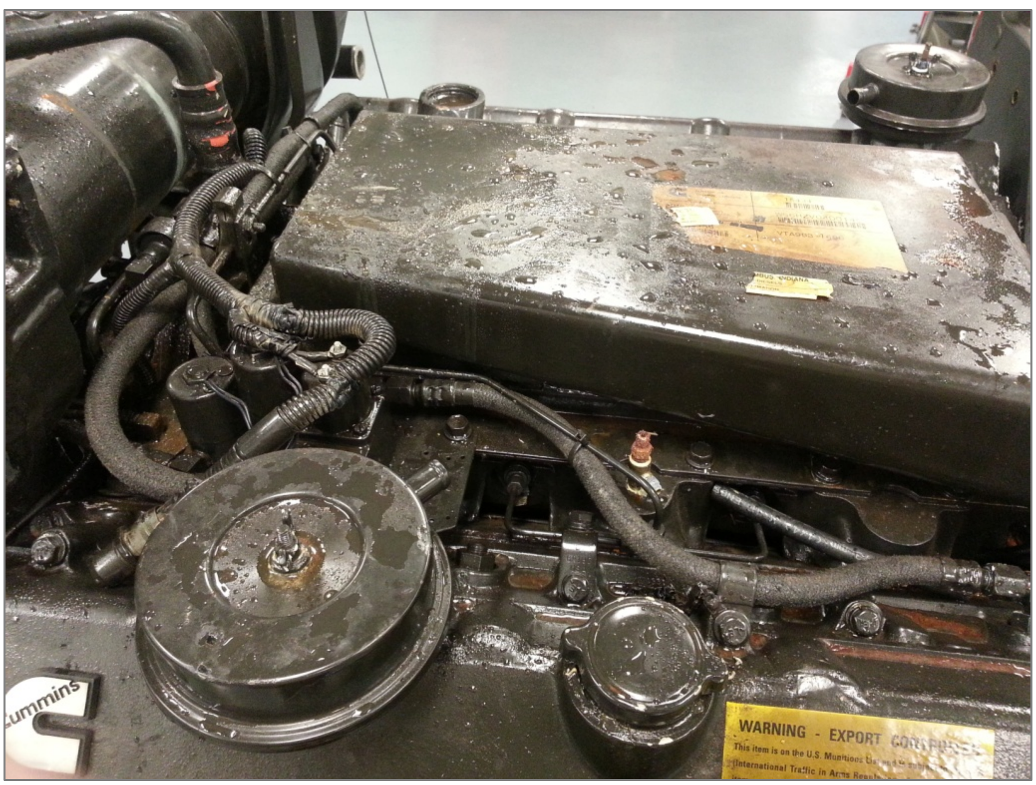

Figure 3. Moisture Accumulated on Engine in Container

Figure 4. Water/Oil Emulsion Present in Container

4.0 RESULTS & DISCUSSION

Discussion and analysis of the tear down and inspection is grouped in four respective sections below: ratings, metrology, photographs, and special investigations.

4.1 RATINGS

Ratings for deposits and wear generally focus around the piston itself, the piston ring pack, and valve tulip deposit formation. These ratings give insight into the ability of an oil to control deposit formation which can have detrimental effects on engine performance if left uncontrolled, as well as give some additional insight into engine wear experienced. Table 1 shows the individual and eight piston average deposit ratings (in demerits).

Table 1. Piston Deposit Summary – 1

	Piston Unweighted Demerits	Top Groove Carbon Demerits	Intermediate Groove Carbon Demerits	Top Land Carbon Demerits	2nd. Land Carbon Demerits
Piston 1	136.75	50.25	30.25	22.75	26.25
Piston 2	142.89	51.50	25.00	23.75	34.75
Piston 3	144.84	58.50	25.00	21.75	29.75
Piston 4	130.18	50.00	25.00	24.75	23.25
Piston 5	139.77	55.50	25.00	25.75	25.25
Piston 6	126.71	51.00	25.00	23.00	19.25
Piston 7	124.36	48.50	25.00	22.00	19.75
Piston 8	151.81	59.50	37.00	23.50	22.75
Average	137.16	53.09	27.16	23.41	25.13

The total unweighted demerit rating for each piston (which acts as the "overall" deposit score) ranges from the mid-120's to just over 150 demerits. The maximum demerit score possible for a piston is dependent on its configuration. For the VTA-903 piston, the maximum score would be 700 demerits, which assumes 100% carbon buildup on all 7 rated locations (groove 1, groove 2, groove 3, undercrown, land 1, land 2, and land 3). If a piston has more than three rings, additional rating locations for the groove and lands would increase the maximum demerit score possible. In general, the VTA-903 deposit ratings where found consistent with trends seen in earlier SCPL development/refinement testing using the General Engine Products (GEP) 6.5L(T) engine (WD17). Likewise, the top groove carbon demerits average just over 50, and the top land demerits average just over 20, which also trend similarly to previous testing results seen on the GEP engine. This shows good consistency with the previous testing, and suggests the oil is exhibiting similar deposit control performance in the VTA-903. However, when comparing the intermediate groove and second land demerits, there does appear to be a higher overall demerit trend than that seen from the GEP testing. While higher, these demerit ratings are still within what would be considered acceptable or normal ranges, and the increase over the GEP engine are likely a result of a configuration difference in the piston and ring pack design of the VTA-903 versus the GEP engine. Without a baseline or reference test to confirm this hypothesis, it is just speculation, but the deposits seen in this area are not of the magnitude to raise any concern over the performance of the SCPL. Table 2 shows additional summary information of the eight piston deposit ratings including top groove fill, more description of the top land deposits (i.e. heavy vs flaked), and piston under crown demerits.

Table 2. Piston Deposit Summary – 2

	Top Groove Fill %	Intermediate Groove Fill %	Top Land Heavy Carbon %	Top Land Flaked Carbon %	Undercrown Demerits
Piston 1	74	43	0	3	2.28
Piston 2	65	57	0	4	1.86
Piston 3	77	58	0	2	1.37
Piston 4	69	46	3	8	2.32
Piston 5	77	48	3	8	2.40
Piston 6	67	45	0	8	2.44
Piston 7	65	43	0	5	2.58
Piston 8	70	49	0	6	2.01
Average	70.50	48.63	0.75	5.50	2.16

The top groove fill ratings were higher for the VTA-903 test than seen during GEP testing. Similarly, the intermediate groove fill was also higher. Top land heavy and flaked carbon showed very low percentages, and piston under crown demerits also showed to be low. These areas generally showed good performance while testing the SCPL candidates in the GEP development, and again suggest overall that the oil is providing good deposit control performance in the VTA-903. There were no instances of stuck rings at the post test teardown on any piston, and the deposit ratings overall appear similar to the good results seen during previous SCPL development testing. Full piston deposit ratings can be seen in Table 3 through Table 18. These include piston by piston deposit ratings, as well supplemental deposit ratings for the ring grooves and rings themselves.

Table 3. Detailed Piston Deposits – Piston #1

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 1

	GROOVE 1			GROOVE 2			GROOVE 3			[redacted]	UNDERCROWN		
	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM		A, %	FCT	DEM
CARBON	2	1.00	2.00	7	1.00	7.00		1.00			[redacted]		
	95	0.50	47.50										
	3	0.25	0.75	93	0.25	23.25		0.25	0.00			0.25	0.00
			50.25	SUBTOTAL		30.25	SUBTOTAL		0.00		SUBTOTAL		
VARNISH			0.00			0.00	45	2.0	0.90		25	2.5	0.63
			0.00			0.00	29	1.0	0.29		50	2.3	1.15
			0.00			0.00	26	0.5	0.13		25	2	0.50
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		1.32		SUBTOTAL		2.28
	TOTAL		50.25	TOTAL		30.25	TOTAL		1.32		TOTAL		2.28
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		50.25	WDP		30.25	WDP		1.32		WDP		2.28

	LAND 1			LAND 2			LAND 3			[redacted]
	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	
CARBON	0	1.00	0.00	5	1.00	5.00		1.00		
	91	0.25	22.75	85	0.25	21.25	4	0.25	1.00	
	SUBTOTAL		22.75	SUBTOTAL		26.25	SUBTOTAL		1.00	
VARNISH	9	9.0	0.81	4	9.0	0.36	4	9.0	0.36	
			0.00	6	3.5	0.21	7	3.5	0.25	
			0.00			0.00	8	2.0	0.16	
			0.00			0.00	25	1.0	0.25	
			0.00			0.00	52	0.5	0.26	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
	100			100			100			
	SUBTOTAL		0.81	SUBTOTAL		0.57	SUBTOTAL		1.28	
	TOTAL		23.56	TOTAL		26.82	TOTAL		2.28	
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	
	WDP		23.56	WDP		26.82	WDP		2.28	

TGC	50.25	WDP	136.75	TLHC	0
2nd.GC	30.25	UWD	136.75	TLFC	3

TGF %	74
IGF %	43

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN	[redacted]	0
PISTON SKIRT		0
LINER		0

Table 4. Detailed Piston Deposits – Piston #1 (Cont.)

SUPPLEMENTAL RATINGS

Piston # 1

		TOP and BOTTOM of GROOVES												
Deposits		HC	**MC**	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	**T**			10	25					40	25			
	B								30	50	20			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	**T**			15	70					15				
	B							25		75				

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	**T**									40	60			
	B									20	80			

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T			5	5						30	20	40	
1	**B**							10					90	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T			5	15						10	10	60	
2	**B**				5					40	20	25	10	
	BK				100									

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T								60		20	20		
3	**B**								50	40	10			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 5. Detailed Piston Deposits – Piston #2

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 2

	GROOVE 1			GROOVE 2			GROOVE 3			UNDERCROWN		
C A	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM
R	4	1.00	4.00		1.00	0.00		1.00	0.00			
B	94	0.50	47.00									
O	2	0.25	0.50	100	0.25	25.00		0.25	0.00		0.25	0.00
N	SUBTOTAL		51.50	SUBTOTAL		25.00	SUBTOTAL		0.00	SUBTOTAL		
V			0.00			0.00	60	1.0	0.60	25	2.5	0.63
A			0.00			0.00	40	0.8	0.32	30	2	0.60
R			0.00			0.00			0.00	35	1.8	0.63
N			0.00			0.00			0.00	10	1.5	0.15
I			0.00			0.00			0.00			0.00
S			0.00			0.00			0.00			0.00
H			0.00			0.00			0.00			0.00
			0.00			0.00			0.00			0.00
	100			100			100			100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		0.92	SUBTOTAL		2.01
	TOTAL		51.50	TOTAL		25.00	TOTAL		0.92	TOTAL		1.86
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1
	WDP		51.50	WDP		25.00	WDP		0.92	WDP		1.86

	LAND 1			LAND 2			LAND 3		
C A									
R	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM
B	0	1.00	0.00	14	1.00	14.00		1.00	0.00
O									
N	95	0.25	23.75	83	0.25	20.75	7	0.25	1.75
	SUBTOTAL		23.75	SUBTOTAL		34.75	SUBTOTAL		1.75
V	5	9.0	0.45	3	3.0	0.09	13	9.0	1.17
A			0.00			0.00	15	3.0	0.45
R			0.00			0.00	45	2.0	0.90
N			0.00			0.00	20	1.5	0.30
I			0.00			0.00			0.00
S			0.00			0.00			0.00
H			0.00			0.00			0.00
			0.00			0.00			0.00
	100			100			100		
	SUBTOTAL		0.45	SUBTOTAL		0.09	SUBTOTAL		2.82
	TOTAL		24.20	TOTAL		34.84	TOTAL		4.57
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1
	WDP		24.20	WDP		34.84	WDP		4.57

TGC	51.50	WDP	142.89	TLHC	0
2nd.GC	25.00	UWD	142.89	TLFC	4

TGF %	65
IGF %	57

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN		0
PISTON SKIRT		0
LINER		0

Table 6. Detailed Piston Deposits – Piston #2 (Cont.)

SUPPLEMENTAL RATINGS

Piston # 2

		TOP and BOTTOM of GROOVES												
Deposits		HC	**MC**	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	**T**			20	30				25	25				
	B									40	60			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	**T**			20	80									
	B				10			20			70			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	**T**								10	20	70			
	B										100			

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T			5	5					25	25	40		
1	**B**								20	10			70	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T			10	15				10	10	55			
2	**B**											40	60	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									90	10			
3	**B**									90	10			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 7. Detailed Piston Deposits – Piston #3

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 3

	GROOVE 1			GROOVE 2			GROOVE 3			[redacted]	UNDERCROWN		
CARBON	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM		A, %	FCT	DEM
	22	1.00	22.00		1.00	0.00		1.00					
	68	0.50	34.00										
	10	0.25	2.50	100	0.25	25.00		0.25	0.00			0.25	0.00
	SUBTOTAL		58.50	SUBTOTAL		25.00	SUBTOTAL		0.00		SUBTOTAL		
VARNISH			0.00			0.00	5	2.0	0.10		10	2.3	0.23
			0.00			0.00	70	1.5	1.05		30	2	0.60
			0.00			0.00	25		0.00		30	1.8	0.54
			0.00			0.00			0.00		30	1	0.30
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		1.15		SUBTOTAL		1.67
	TOTAL		58.50	TOTAL		25.00	TOTAL		1.15		TOTAL		1.37
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		58.50	WDP		25.00	WDP		1.15		WDP		1.37

	LAND 1			LAND 2			LAND 3			[redacted]
CARBON	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	
	0	1.00	0.00	8	1.00	8.00		1.00	0.00	
	87	0.25	21.75	87	0.25	21.75	15	0.25	3.75	
	SUBTOTAL		21.75	SUBTOTAL		29.75	SUBTOTAL		3.75	
VARNISH	10	9.0	0.90	2	9.0	0.18	8	9.0	0.72	
	3	5.5	0.17	3	4.2	0.13	28	2.2	0.62	
			0.00			0.00	42	1.8	0.76	
			0.00			0.00	7	1.5	0.11	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
	100			100			100			
	SUBTOTAL		1.07	SUBTOTAL		0.31	SUBTOTAL		2.20	
	TOTAL		22.82	TOTAL		30.06	TOTAL		5.95	
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	
	WDP		22.82	WDP		30.06	WDP		5.95	

TGC	58.50	WDP	144.84	TLHC	0
2nd. GC	25.00	UWD	144.84	TLFC	2

TGF %	77
IGF %	58

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN	[redacted]	0
PISTON SKIRT		0
LINER		0

Table 8. Detailed Piston Deposits – Piston #3 (Cont.)

SUPPLEMENTAL RATINGS

Piston #	3

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	T			40	50					10				
	B									80	20			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	T			25	35				20	20				
	B								60	40				

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	T								20	60	20			
	B									85	15			

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T			5	5						45		45	
1	B												100	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				30								70	
2	B											20	80	
	BK	10		90										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									70	30			
3	B									40	60			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.
Anti.Thrust Skirt has plating removal 5%.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 9. Detailed Piston Deposits – Piston #4

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 4

	GROOVE 1			GROOVE 2			GROOVE 3				UNDERCROWN		
C A R B O N	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	[redacted]	A, %	FCT	DEM
	10	1.00	10.00		1.00	0.00		1.00					
	73	0.50	36.50										
	14	0.25	3.50	100	0.25	25.00		0.25	0.00			0.25	0.00
	SUBTOTAL		50.00	SUBTOTAL		25.00	SUBTOTAL		0.00		SUBTOTAL		
V A R N I S H	3	4.2	0.13			0.00	30	2.0	0.60		45	2.5	1.13
			0.00			0.00	52	0.8	0.42		30	2.3	0.69
			0.00			0.00	18	0.5	0.09		25	2	0.50
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.13	SUBTOTAL		0.00	SUBTOTAL		1.11		SUBTOTAL		2.32
	TOTAL		50.13	TOTAL		25.00	TOTAL		1.11		TOTAL		2.32
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		50.13	WDP		25.00	WDP		1.11		WDP		2.32

	LAND 1			LAND 2			LAND 3			
C A R B O N	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	[redacted]
	3	1.00	3.00		1.00	0.00		1.00	0.00	
	87	0.25	21.75	93	0.25	23.25	5	0.25	1.25	
	SUBTOTAL		24.75	SUBTOTAL		23.25	SUBTOTAL		1.25	
V A R N I S H	4	9.0	0.36	7	9.0	0.63	10	3.0	0.30	
	6	5.0	0.30			0.00	37	1.5	0.56	
			0.00			0.00	48	0.5	0.24	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
			0.00			0.00			0.00	
	100			100			100			
	SUBTOTAL		0.66	SUBTOTAL		0.63	SUBTOTAL		1.10	
	TOTAL		25.41	TOTAL		23.88	TOTAL		2.35	
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	
	WDP		25.41	WDP		23.88	WDP		2.35	

TGC	50.13	WDP	130.18	TLHC	3
2nd.GC	25.00	UWD	130.18	TLFC	8

TGF %	69
IGF %	46

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN	[redacted]	0
PISTON SKIRT		0
LINER		0

Table 10. Detailed Piston Deposits – Piston #4 (Cont.)

SUPPLEMENTAL RATINGS

Piston # 4

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	T			20	70					10				
	B								30	50	20			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	T			70	30									
	B							10		60	30			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	T									35	65			
	B										100			

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									45	10	45		
1	B										10		90	
	BK				100									

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T						10	20	10	15	10		35	
2	B										60	20	20	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									45	10	45		
3	B										10		90	
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 11. Detailed Piston Deposits – Piston #5

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 5

	GROOVE 1			GROOVE 2			GROOVE 3			UNDERCROWN		
	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM
CARBON	13	1.00	13.00		1.00	0.00		1.00				
	83	0.50	41.50									
	4	0.25	1.00	100	0.25	25.00		0.25	0.00		0.25	0.00
	SUBTOTAL		55.50	SUBTOTAL		25.00	SUBTOTAL		0.00	SUBTOTAL		
VARNISH			0.00			0.00	25	2.0	0.50	40	2.7	1.08
			0.00			0.00	50	1.2	0.60	40	2.3	0.92
			0.00			0.00	25	0.5	0.13	20	2	0.40
			0.00			0.00			0.00			0.00
			0.00			0.00			0.00			0.00
			0.00			0.00			0.00			0.00
			0.00			0.00			0.00			0.00
			0.00			0.00			0.00			0.00
	100			100			100			100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		1.23	SUBTOTAL		2.40
	TOTAL		55.50	TOTAL		25.00	TOTAL		1.23	TOTAL		2.40
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1
	WDP		55.50	WDP		25.00	WDP		1.23	WDP		2.40

	LAND 1			LAND 2			LAND 3		
	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM
CARBON	3	1.00	3.00	5	1.00	5.00		1.00	0.00
	91	0.25	22.75	81	0.25	20.25	3	0.25	0.75
	SUBTOTAL		25.75	SUBTOTAL		25.25	SUBTOTAL		0.75
VARNISH	6	5.8	0.35	11	9.0	0.99	2	9.0	0.18
			0.00	3	4.0	0.12	26	2.8	0.73
			0.00			0.00	49	2.3	1.13
			0.00			0.00	20	2.0	0.40
			0.00			0.00			0.00
			0.00			0.00			0.00
			0.00			0.00			0.00
			0.00			0.00			0.00
	100			100			100		
	SUBTOTAL		0.35	SUBTOTAL		1.11	SUBTOTAL		2.44
	TOTAL		26.10	TOTAL		26.36	TOTAL		3.19
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1
	WDP		26.10	WDP		26.36	WDP		3.19

TGC	55.50	WDP	139.77	TLHC	3
2nd.GC	25.00	UWD	139.77	TLFC	8

TGF %	77
IGF %	48

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN		0
PISTON SKIRT		0
LINER		0

Table 12. Detailed Piston Deposits – Piston #5 (Cont.)

SUPPLEMENTAL RATINGS

Piston # 5

		TOP and BOTTOM of GROOVES												
Deposits		HC	**MC**	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	**T**			60	40									
	B								30	30	40			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	**T**			40	30				15	15				
	B			10	10			25	25	30				

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	**T**									30	70			
	B								20	35	45			

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									10	30	20	40	
1	**B**									10		10	80	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									5	5	10	80	
2	**B**				5						45	30	20	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T									40	50	10		
3	**B**									15	85			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 13. Detailed Piston Deposits – Piston #6

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 6

	GROOVE 1			GROOVE 2			GROOVE 3				UNDERCROWN		
C										[redacted]			
A	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM		A, %	FCT	DEM
R	6	1.00	6.00		1.00	0.00		1.00			[redacted]		
B O	86	0.50	43.00										
N	8	0.25	2.00	100	0.25	25.00		0.25	0.00			0.25	0.00
	SUBTOTAL		51.00	SUBTOTAL		25.00	SUBTOTAL		0.00		SUBTOTAL		
V			0.00			0.00	20	1.0	0.20		50	2.7	1.35
A			0.00			0.00	80	0.5	0.40		30	2.3	0.69
R			0.00			0.00			0.00		20	2	0.40
N			0.00			0.00			0.00				0.00
I			0.00			0.00			0.00				0.00
S			0.00			0.00			0.00				0.00
H			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		0.60		SUBTOTAL		2.44
	TOTAL		51.00	TOTAL		25.00	TOTAL		0.60		TOTAL		2.44
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		51.00	WDP		25.00	WDP		0.60		WDP		2.44

	LAND 1			LAND 2			LAND 3			
C A										[redacted]
R	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	
B	0	1.00	0.00		1.00	0.00		1.00	0.00	
O										
N	92	0.25	23.00	77	0.25	19.25	5	0.25	1.25	
	SUBTOTAL		23.00	SUBTOTAL		19.25	SUBTOTAL		1.25	
V	8	9.0	0.72	5	9.0	0.45	2	9.0	0.18	
A			0.00	13	8.0	1.04	5	6.5	0.33	
R			0.00	5	2.2	0.11	25	2.7	0.68	
N			0.00			0.00	35	1.5	0.53	
I			0.00			0.00	28	0.5	0.14	
S			0.00			0.00			0.00	
H			0.00			0.00			0.00	
			0.00			0.00			0.00	
	100			100			100			
	SUBTOTAL		0.72	SUBTOTAL		1.60	SUBTOTAL		1.85	
	TOTAL		23.72	TOTAL		20.85	TOTAL		3.10	
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	
	WDP		23.72	WDP		20.85	WDP		3.10	

TGC	51.00	WDP	126.71	TLHC	0
2nd.GC	25.00	UWD	126.71	TLFC	8

TGF %	67
IGF %	45

	Ring Stuck ?	Scuffed Area %
TOP RING	N0	0
2nd. RING	N0	0
OIL RING	N0	0
PISTON CROWN	[redacted]	0
PISTON SKIRT		0
LINER		0

Table 14. Detailed Piston Deposits – Piston #6 (Cont.)

SUPPLEMENTAL RATINGS

Piston #	6

		TOP and BOTTOM of GROOVES												
Deposits		HC	**MC**	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	**T**			40	60									
	B								10	40	50			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	**T**			25	10			30		35				
	B									65	35			

		TOP and BOTTOM of GROOVES												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	**T**									25	75			
	B										100			

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				5						10	10	45	
1	**B**										5		95	
	BK			100										

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				30						10		60	
2	**B**									20	45	10	25	
	BK													

		TOP, BOTTOM and BACK of RINGS												
Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				5				20	30	45			
3	**B**									40	60			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 15. Detailed Piston Deposits – Piston #7

Engine:		Date Rated	04/23/13
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 7

	GROOVE 1			GROOVE 2			GROOVE 3				UNDERCROWN		
C A	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM		A, %	FCT	DEM
R	1	1.00	1.00		1.00	0.00		1.00					
B O	91	0.50	45.50										
N	8	0.25	2.00	100	0.25	25.00		0.25	0.00			0.25	0.00
	SUBTOTAL		48.50	SUBTOTAL		25.00	SUBTOTAL		0.00		SUBTOTAL		
V			0.00			0.00	10	2.0	0.20		45	2.8	1.26
A			0.00			0.00	72	1.0	0.72		25	2.5	0.63
R			0.00			0.00	18	0.5	0.09		30	2.3	0.69
N			0.00			0.00			0.00				0.00
I			0.00			0.00			0.00				0.00
S			0.00			0.00			0.00				0.00
H			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		1.01		SUBTOTAL		2.58
	TOTAL		48.50	TOTAL		25.00	TOTAL		1.01		TOTAL		2.58
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		48.50	WDP		25.00	WDP		1.01		WDP		2.58

	LAND 1			LAND 2			LAND 3		
C A R	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM
B	0	1.00	0.00		1.00	0.00		1.00	0.00
O									
N	88	0.25	22.00	79	0.25	19.75	4	0.25	1.00
	SUBTOTAL		22.00	SUBTOTAL		19.75	SUBTOTAL		1.00
V	7	9.0	0.63	7	9.0	0.63	12	3.0	0.36
A	5	5.0	0.25	5	4.5	0.23	71	2.7	1.92
R			0.00	9	2.8	0.25	13	2.0	0.26
N			0.00			0.00			0.00
I			0.00			0.00			0.00
S			0.00			0.00			0.00
H			0.00			0.00			0.00
			0.00			0.00			0.00
	100			100			100		
	SUBTOTAL		0.88	SUBTOTAL		1.11	SUBTOTAL		2.54
	TOTAL		22.88	TOTAL		20.86	TOTAL		3.54
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1
	WDP		22.88	WDP		20.86	WDP		3.54

TGC	48.50	WDP	124.36	TLHC	0
2nd.GC	25.00	UWD	124.36	TLFC	5

TGF %	65
IGF %	43

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN		0
PISTON SKIRT		0
LINER		0

Table 16. Detailed Piston Deposits – Piston #7 (Cont.)

SUPPLEMENTAL RATINGS

Piston #	7

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	T			45	20		25	10						
	B									10	90			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	T				45	30				15	10			
	B									10	90			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	T										100			
	B										100			

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				5						40	20	35	
1	B												100	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				15				30	15	15		25	
2	B				5					30	35		30	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T						10	15		55	20			
3	B									30	45	25		
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

Table 17. Detailed Piston Deposits – Piston #8

Engine:		Date Rated	
Oil Code:		HOURS	
		RATER	RBV

PISTON DEPOSIT RATING WORKSHEET

PISTON NUMBER: 8

C	GROOVE 1			GROOVE 2			GROOVE 3			[redacted]	UNDERCROWN		
A	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM		A, %	FCT	DEM
R	22	1.00	22.00	16	1.00	16.00		1.00					
B	72	0.50	36.00										
O	6	0.25	1.50	84	0.25	21.00		0.25	0.00			0.25	0.00
N	SUBTOTAL		59.50	SUBTOTAL		37.00	SUBTOTAL		0.00		SUBTOTAL		
V			0.00			0.00	25	2.2	0.55		35	2.7	0.95
A			0.00			0.00	48	1.5	0.72		25	2.5	0.63
R			0.00			0.00	27	0.5	0.14		20	2.2	0.44
N			0.00			0.00			0.00		20	1.8	0.36
I			0.00			0.00			0.00				0.00
S			0.00			0.00			0.00				0.00
H			0.00			0.00			0.00				0.00
			0.00			0.00			0.00				0.00
	100			100			100				100		
	SUBTOTAL		0.00	SUBTOTAL		0.00	SUBTOTAL		1.41		SUBTOTAL		2.37
	TOTAL		59.50	TOTAL		37.00	TOTAL		1.41		TOTAL		2.01
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1		LOC FACTOR		1
	WDP		59.50	WDP		37.00	WDP		1.41		WDP		2.01

C	LAND 1			LAND 2			LAND 3			[redacted]
A										
R	A, %	FCT	DEM	A, %	FCT	DEM	A, %	FCT	DEM	
B	0	1.00	0.00	2	1.00	2.00		1.00		
O										
N	94	0.25	23.50	83	0.25	20.75	6	0.25	1.50	
	SUBTOTAL		23.50	SUBTOTAL		22.75	SUBTOTAL		1.50	
V	6	9.0	0.54	8	6.5	0.52	13	9.0	1.17	
A			0.00	7	3.3	0.23	3	5.5	0.17	
R			0.00			0.00	48	2.0	0.96	
N			0.00			0.00	2	2.5	0.05	
I			0.00			0.00	28	1.8	0.50	
S			0.00			0.00			0.00	
H			0.00			0.00			0.00	
			0.00			0.00			0.00	
	100			100			100			
	SUBTOTAL		0.54	SUBTOTAL		0.75	SUBTOTAL		2.85	
	TOTAL		24.04	TOTAL		23.50	TOTAL		4.35	
	LOC FACTOR		1	LOC FACTOR		1	LOC FACTOR		1	
	WDP		24.04	WDP		23.50	WDP		4.35	

TGC	59.50	WDP	151.81	TLHC	0
2nd.GC	37.00	UWD	151.81	TLFC	6

TGF %	70
IGF %	49

	Ring Stuck ?	Scuffed Area %
TOP RING	NO	0
2nd. RING	NO	0
OIL RING	NO	0
PISTON CROWN	[redacted]	0
PISTON SKIRT		0
LINER		0

Table 18. Detailed Piston Deposits – Piston #8 (Cont.)

SUPPLEMENTAL RATINGS

Piston # 8

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
1	T			20					25	25				
	B									20	80			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
2	T			35					40	25				
	B			10	5					40	45			

TOP and BOTTOM of GROOVES

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
3	T									40	60			
	B									30	70			

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				5						55	40		
1	B									5			95	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T				15				20		10	15	40	
2	B				5					10	10	40	35	
	BK			100										

TOP, BOTTOM and BACK of RINGS

Deposits		HC	MC	LC	9.0 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	0.9 - 0.1	Clean
	T							10	20	30	30	10		
3	B								15	10	75			
	BK				100									

PISTON CONDITION: Thrust & Ant. Thrust Skirt have light vertical line scratches.

RING CONDITION: Normal.

LINER CONDITION:

COMMENTS:

In addition to piston and ring deposit ratings, the VTA-903's exhaust and intake valve tulips were rated for deposits. Unlike the piston ratings, valve ratings are in terms of merits and not demerits. Thus, a higher number indicates a better score, or lower overall deposit rating. Complete valve tulip ratings can be seen below in Table 19.

Table 19. Valve Tulip Deposit Ratings

Valve Rating

Test No.: ________________

Exhaust Valves

Cyl. No.	1	2	3	4	5	6	7	8	Average
Left	8.0	8.2	8.0	8.0	8.1	8.1	8.2	8.2	8.07
Right	8.0	8.2	8.1	8.0	8.0	8.1	8.0	8.1	8.07
					Total Average				**8.07**

Intake Valves

Cyl. No.	1	2	3	4	5	6	7	8	Average
Left	7.9	7.5	7.8	7.6	8.0	7.8	8.5	9.1	7.77
Right	8.3	7.5	8.0	7.6	8.6	8.5	8.1	8.8	8.08
					Total Average				**7.93**

Exhaust Valves (Cylinder Average)

	1	2	3	4	5	6	7	8
Average	**8.0**	**8.2**	**8.1**	**8.0**	**8.1**	**8.1**	**8.1**	**8.2**

Intake Valves (Cylinder Average)

	1	2	3	4	5	6	7	8
Average	**8.1**	**7.5**	**7.9**	**7.6**	**8.3**	**8.2**	**8.3**	**9.0**

In general, we see a total average of 8.07 merits for the exhaust valves, and 7.93 merits for the intake valves. This again shows to be consistent with valve deposit ratings for the GEP development testing, and is overall considered a good result. Interestingly (and differently than the GEP testing), there was a propensity for a very light weight flaked carbon deposit to form in the intake valve tulips. This deposit formation was very light and fragile at the time of inspection, which resulted in a small collection of loose flakes in many of the intake port areas after cylinder head disassembly. As much of these deposits were retained on the valve as possible through careful handling, but with its overall fragility, some deposits did fall off of the valve before ratings. An example of this phenomenon can be seen below in Figure 5. Although present, these deposits do not immediately raise any cause for concern. At this time it is inconclusive if the valve tulip deposits were this loose immediately upon test completion, or if this is a result of the length of time the engine remained in storage between test EOT and teardown. Moisture apparent in the engine shipping container during storage could have contributed to the breakdown of more solid deposits on the valve tulips resulting in these light loose flakes, as with the fragility of these deposits, none would have been expected to stay intact while the engine was being operated. This further suggests the formation (or breakdown) occurred while the engine was in storage.

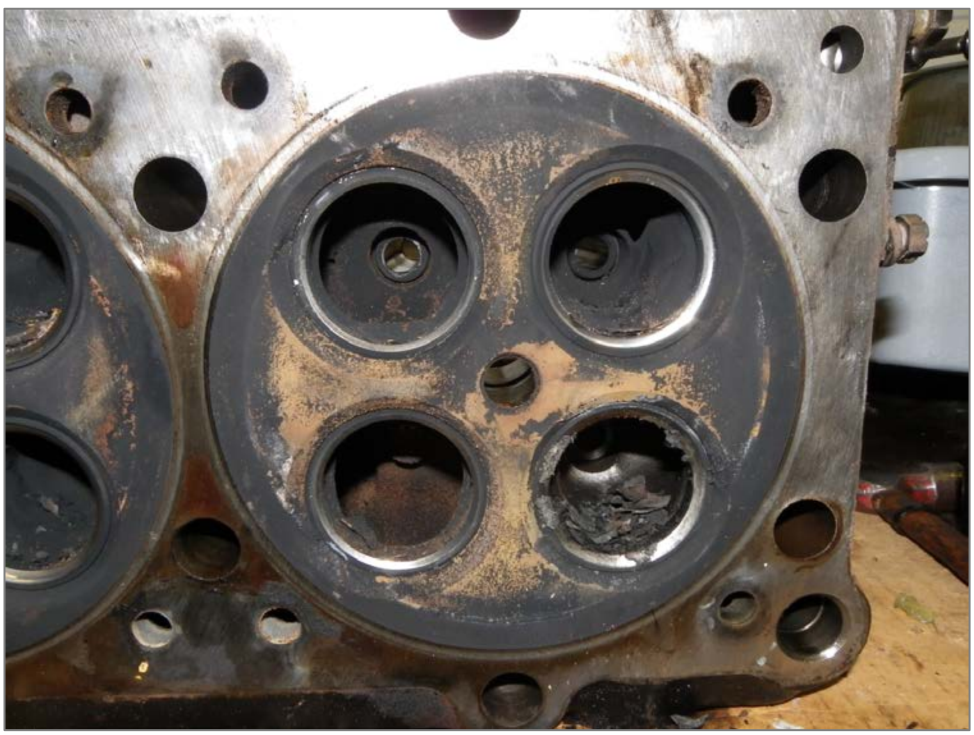

Figure 5. Intake Port Light Flaked Carbon Deposits (Loose)

Since full pre-test metrology data was not available on this engine to quantify engine wear, some additional ratings were completed to help assess engine wear trends in addition to the more standard deposit ratings. These included visual ratings of the cylinder liners for scuffing and polish, and ratings for the valve cross heads for distress. Full liner bore ratings can be seen below in Table 20. In short, none of the liners showed any notable scuffing or bore polish. As noted in the comments section of the ratings, each liner showed some light vertical scratches on the thrust and anti-trust side, which is consistent with normal use, and complements the light scratches reported on the piston skirts in the full piston ratings.

Table 20. Liner Bore Ratings for Scuffing & Polish

Test No.: ________ Test Hours: ________

Oil Code: ________ Rater RBV

Cylinder Liner

Percent Of Total Ring Travel Area

	% Scuffing			Bore Polished		% Avg.Area
Cyl. #	T	AT	% Avg.Area Scuffed	T	AT	Bore Polish
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
Avg.	0	0	0	0	0	0

Comments: On all liners have a few light vertical line scratchs on both the Thrust and Anti.Thrust side of each liner.

The valve cross heads did show visual wear, which is consistent and normal for a used engine. This area is a known critical area for several engines in the Cummins engine family. Overall, the distress ratings ranged from a number 6 to number 8 rating, which coincides with a range of trace to light (8) and light to medium (6) distress. Trace distress is in general barely discernible, and can require a 10x magnification to fully assess condition. Light distress is more prominent, and can be seen without magnification, but is still much lighter than a medium, heavy, or catastrophic distress level. Full cross head ratings can be seen below in Table 21. Overall the condition of the cross heads was found to be good, and results suggest that the SCPL candidate provided adequate protection for this critical engine interface.

Full photographs of each of these rated components can be seen in section 3.3 of this report entitled "Photographs."

Table 21. Valve Cross Head Ratings

Cyl #		Numerical Value
1	INTAKE	6
	EXHAUST	7
2	INTAKE	7
	EXHAUST	7
3	INTAKE	6
	EXHAUST	8
4	INTAKE	8
	EXHAUST	7
5	INTAKE	7
	EXHAUST	8
6	INTAKE	7
	EXHAUST	8
7	INTAKE	6
	EXHAUST	8
8	INTAKE	7
	EXHAUST	8

4.2 METROLOGY

Post test engine measurements, or metrology, was conducted on the Cummins 903 engine to try and gain an additional understanding of physical engine wear experienced during the SCPL evaluation. As noted in the TARDEC engine test report, the Cummins 903 engine was sourced and tested as received directly from the engine supplier (source unknown to authors), and no pre test inspection or metrology process was completed. Despite this, some post test measurements were completed by TFLRF to allow for general comparison to expected or normal measurement ranges, as well as wear limits for the engine. All quoted measurement ranges and wear limits herein were sourced from the direct support and general support maintenance manual TM9-2815-219-34, entitled "Engine, Diesel: Liquid Cooled V-Type Eight Cylinder Turbocharged Cummins Model VTA-93 With Engine Container Assembly." [4]. Metrology results are summarized in the bulleted list below with respective comments added. Full metrology tables are included in an appendix to this report.

- Cylinder Bore Diameter
  Wear limit >5.505in, 0.003in eccentricity [4, pg 4-128]
  - Liner bores from test engine measured thrust and anti-thrust @ 25mm from top, 105mm from top, and 180mm from top (i.e. top, middle, bottom)
  - All bore measurements were below established wear limits, and within specified eccentricity
  - Measurements ranged from a maximum of 5.4997in to a minimum of 5.0519in
- Piston Skirt Diameter
  Expected skirt diameter of 5.485in to 5.490in [4, pg 4-122]
  - Skirt diameter measured at bottom of piston skirt for each piston
  - Measurements varied between 5.4880in to 5.4884in, within established limits
- Calculated Line Bore to Skirt Clearance
  Specified clearance of 0.0095in to 0.017in [3, pg 4-123]
  - Average bore diameters calculated from individual liner measurements, and compared to piston skirt diameters to verify liner clearance at each location
  - Measurements ranged from 0.0119in to 0.0147in, within established limits

- Piston Ring End Gaps

  Specified at: [4, pg 4-135]

  Top: 0.017in to 0.027in

  Second: 0.013in to 0.023in

  Oil Control: 0.010in to 0.025in

  - Ring end gaps measured in their respective liner bores
  - Top ring end gap varied from 0.020in to 0.022in, within established limits
  - Second ring end gap varied from 0.022in to 0.029in, with four rings (Cylinder 2,3,5,6) outside limits listed in TM.
  - Oil control ring end gap varied from 0.019in to 0.022in, within established limits

- Piston Ring to Groove Clearance

  Reference ranges not specified in TM

  - Only oil control ring measured, as not to disturb deposits on the top and second rings
  - Oil control ring to groove clearance ranged from 0.002in to 0.003in for all cylinders

- Piston Pin Diameter

  Wear limit <1.748in

  - Pin diameter measured in contact area at rod and piston interface
  - Pin diameter in rod area varied from 1.7486in to 1.7487in, within established limits
  - Pin diameter in piston area varied from 1.7488in to 1.7489in, within established limits

- Piston Pin Bore Diameter

  Established wear limit 1.750in, maximum [4, pg 4-123]

  - Measurements ranged from 1.7496in to 1.7497in, within established limits

- Connection Rod Pin Bore Diameter

  Expected range of 1.7510in to 1.7515in [4, pg 4-117]

  - Pin bore in rod ranged from 1.7510in to 1.7515in, within established limits

- Calculated Pin to Bore Clearance at Connecting Rod
  Estimated maximum of 0.0035in per max rod busing ID, and min pin diameter specified above
  - Measurements ranged from 0.0023in to 0.0027in, within established limits
- Calculated Pin to Bore Clearance at Piston
  Estimated maximum of 0.002in per max piston pin bore ID, and min pin diameter specified above
  - Measurements ranged from 0.0007in to 0.0008in, within established limits
- Main Bearing Clearance
  No specific bearing clearances noted in TM, only specified journal and bore diameters
  - Measurements of post-test main bearing clearance ranged from 0.0035in to 0.004in, which appear reasonable for the engine

From the metrology data reported, we can conclude that the engine mechanically remained in good condition throughout testing. Apart from the isolated 2nd ring end gaps that were outside the specified range, all measurements fell within the recommended service ranges called out for the VTA-903 engine in its respective technical manual [4].

The four particular ring end gap measurements that were found out of specification only varied 0.003in to 0.006in over the normal expected range. This small of a deviation does not bring up any immediate concern over the performance of the candidate SCPL, and without the pre-test metrology data to confirm conformance when starting, could very likely have existed after rebuild. In general, changes in ring end gap measurements during testing are a result of ring face wear (i.e. ring radial thickness) and an increase in liner bore diameter as a result of wear.

All of these metrology results, like the results seen in the ratings section, support that the candidate SCPL is providing adequate hardware protection to the engine, and can be expected to provide good performance to the VTA-903 engine family, despite its reduced viscosity over normal heavy duty diesel engine oils. All detailed engine metrology data is attached as an appendix to this report.

4.3 PHOTOGRAPHS

Photographs of major engine components were taken to document visual condition of internal components. These photos complement the metrology and ratings information reported above, and are shown in the various sub-sections below:

4.3.1 Liner Bore

Each liner bore was photographed along its thrust and anti-thrust surfaces for comparison, and are shown in Figure 6 through Figure 21. Each is labeled to identify its location (i.e. cylinder number) on the engine. As seen in the ratings results, none of the individual liners showed evidence of scuffing or bore polish. All lines showed light vertical scratches consistent with normal operation.

Figure 6. Liner Bore, Cylinder #1, Thrust

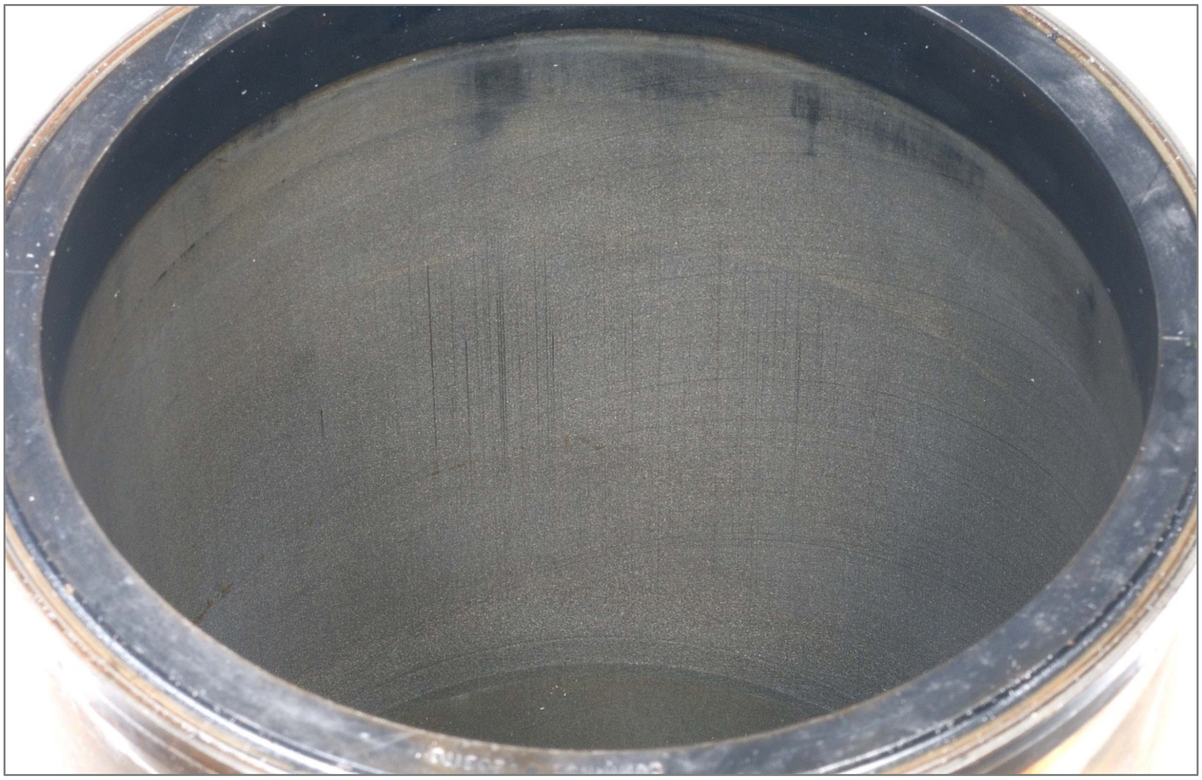

Figure 7. Liner Bore, Cylinder #1, Anti-Thrust

Figure 8. Liner Bore, Cylinder #2, Thrust

Figure 9. Liner Bore, Cylinder #2, Anti-Thrust

Figure 10. Liner Bore, Cylinder #3, Thrust

Figure 11. Liner Bore, Cylinder #3, Anti-Thrust

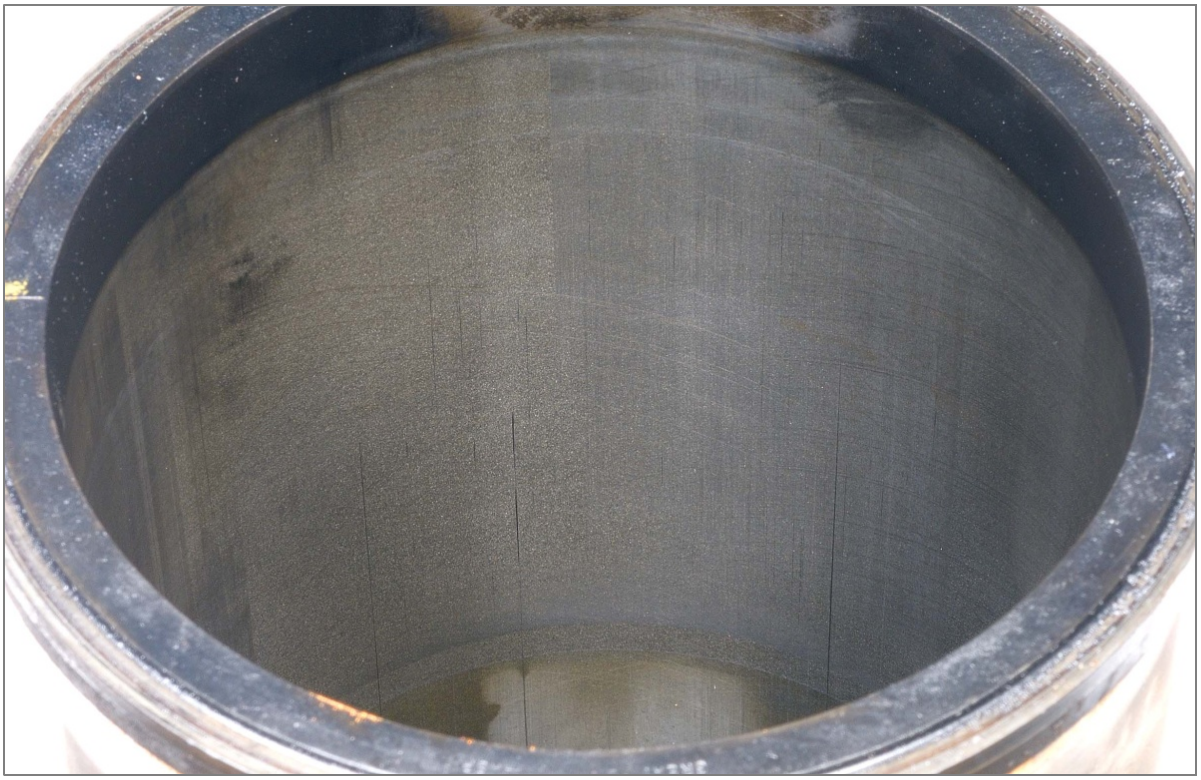

Figure 12. Liner Bore, Cylinder #4, Thrust

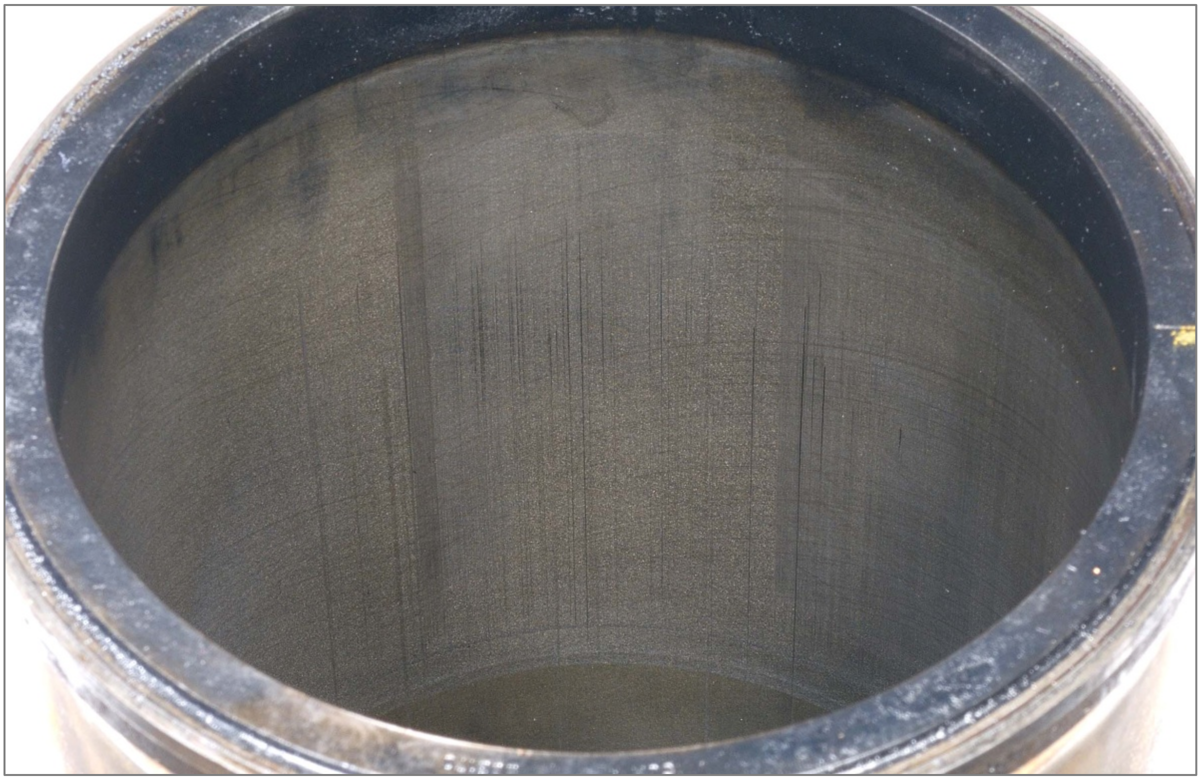

Figure 13. Liner Bore, Cylinder #4, Anti-Thrust

Figure 14. Liner Bore, Cylinder #5, Thrust

Figure 15. Liner Bore, Cylinder #5, Anti-Thrust

Figure 16. Liner Bore, Cylinder #6, Thrust

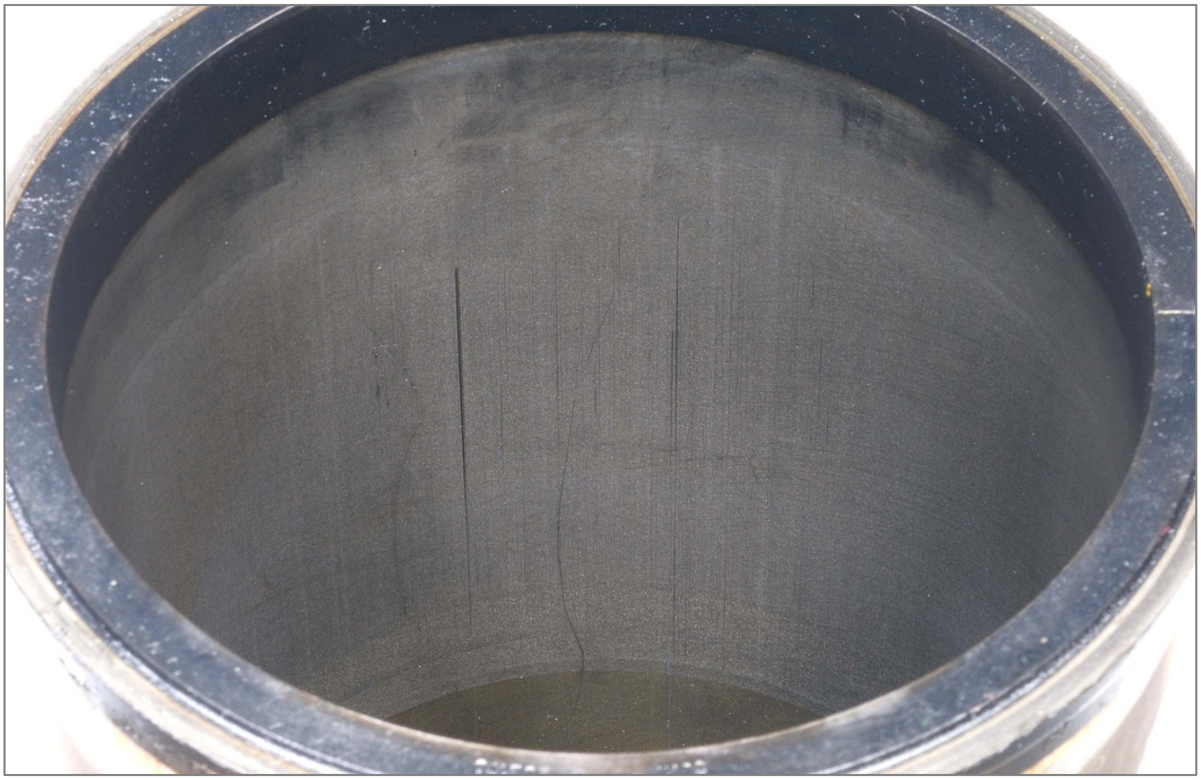

Figure 17. Liner Bore, Cylinder #6, Anti-Thrust

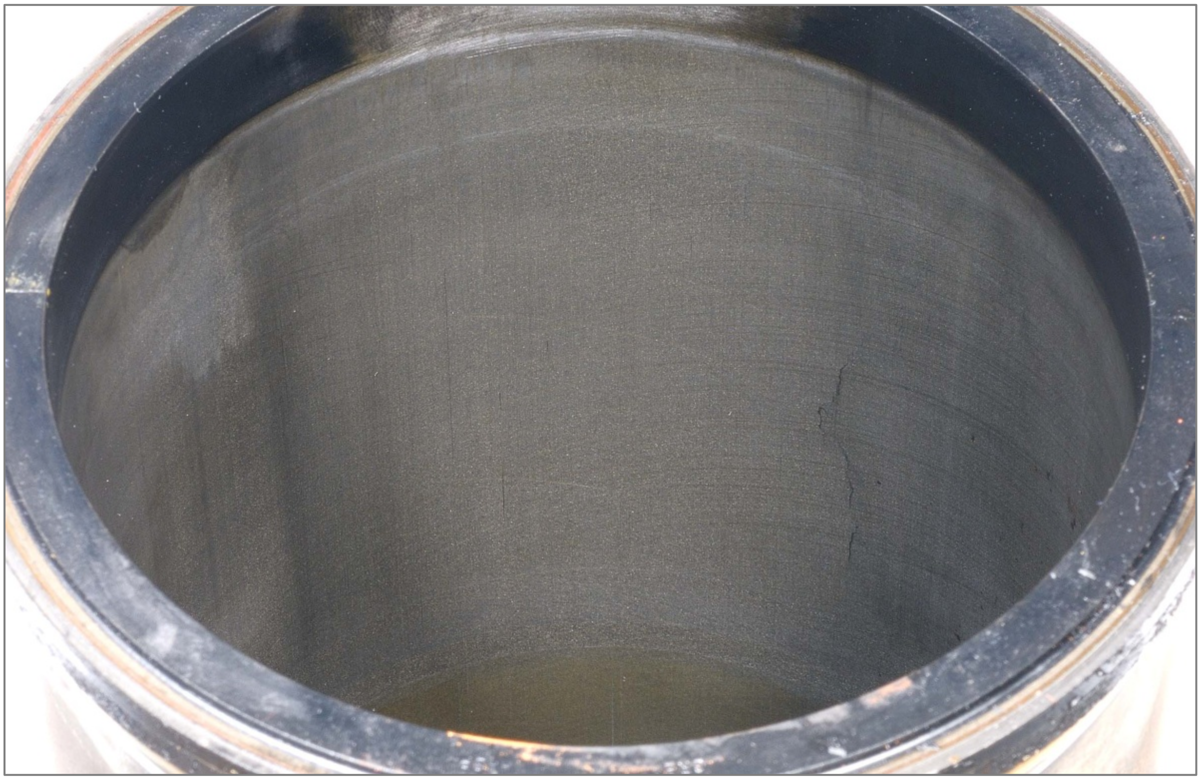

Figure 18. Liner Bore, Cylinder #7, Thrust

Figure 19. Liner Bore, Cylinder #7, Anti-Thrust

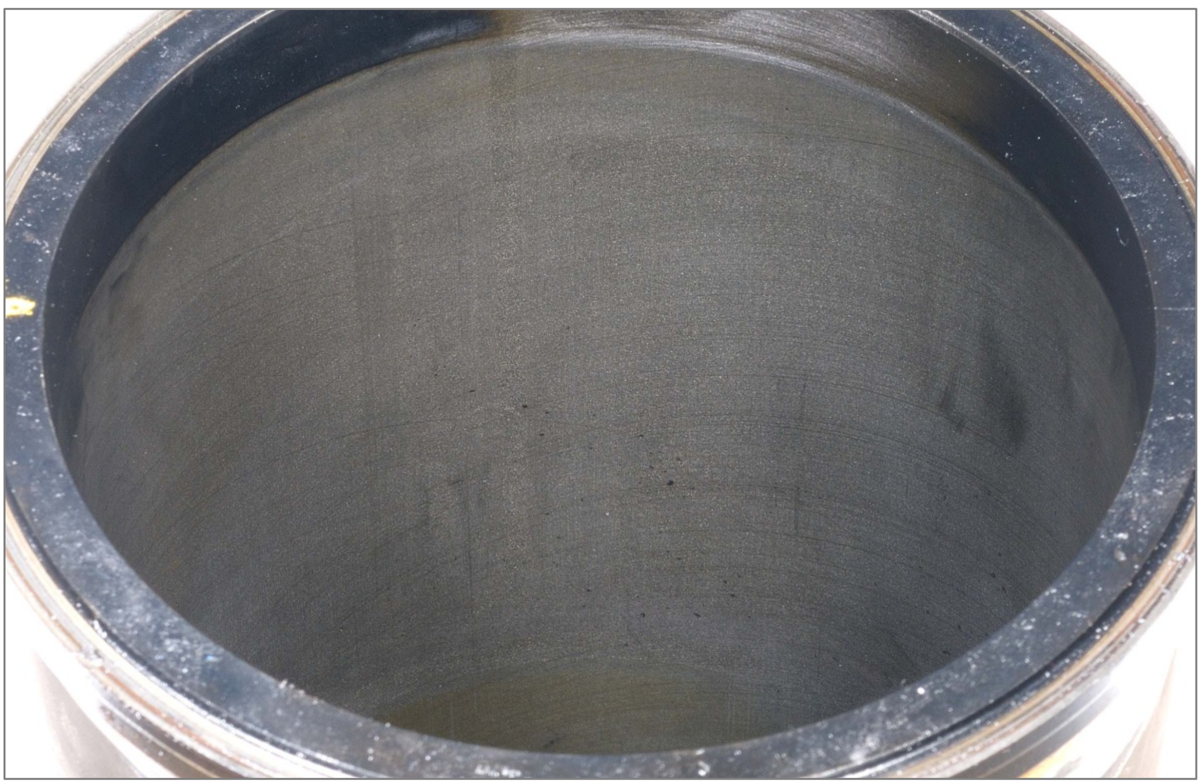

Figure 20. Liner Bore, Cylinder #8, Thrust

Figure 21. Liner Bore, Cylinder #8, Anti-Thrust

4.3.2 Piston

Photographs of each piston include the thrust and anti-thrust views of the piston skirt, as well as photos of the piston bowl and under crowns (Figure 22 through Figure 53).

Figure 22. Piston Skirt, Cylinder #1, Thrust

Figure 23. Piston Skirt, Cylinder #1, Anti-Thrust

Figure 24. Piston Crown, Cylinder #1

Figure 25. Piston Undercrown, Cylinder #1

Figure 26. Piston Skirt, Cylinder #2, Thrust

Figure 27. Piston Skirt, Cylinder #2, Anti-Thrust

Note, rust/water markings shown in the bowl of the number two piston looks to have occurred during the length of storage.

Figure 28. Piston Crown, Cylinder #2

Figure 29. Piston Undercrown, Cylinder #2

Figure 30. Piston Skirt, Cylinder #3, Thrust

Figure 31. Piston Skirt, Cylinder #3, Anti-Thrust

Figure 32. Piston Crown, Cylinder #3

Figure 33. Piston Undercrown, Cylinder #3

Figure 34. Piston Skirt, Cylinder #4, Thrust

Figure 35. Piston Skirt, Cylinder #4, Anti-Thrust

Figure 36. Piston Crown, Cylinder #4

Figure 37. Piston Undercrown, Cylinder #4

Figure 38. Piston Skirt, Cylinder #5, Thrust

Figure 39. Piston Skirt, Cylinder #5, Anti-Thrust

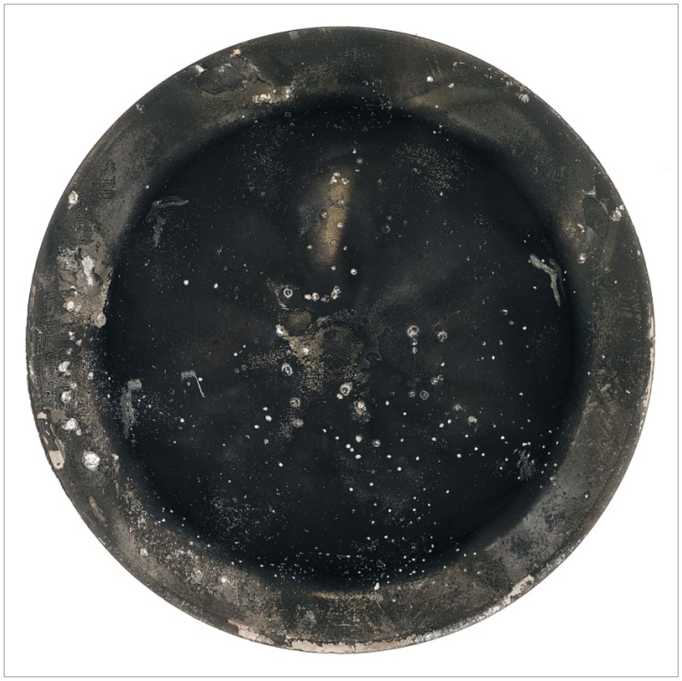

Figure 40. Piston Crown, Cylinder #5

Figure 41. Piston Undercrown, Cylinder #5

Figure 42. Piston Skirt, Cylinder #6, Thrust

Figure 43. Piston Skirt, Cylinder #6, Anti-Thrust

Figure 44. Piston Crown, Cylinder #6

Figure 45. Piston Undercrown, Cylinder #6

Figure 46. Piston Skirt, Cylinder #7, Thrust

Figure 47. Piston Skirt, Cylinder #7, Anti-Thrust

Figure 48. Piston Crown, Cylinder #7

Figure 49. Piston Undercrown, Cylinder #7

Figure 50. Piston Skirt, Cylinder #8, Thrust

Figure 51. Piston Skirt, Cylinder #8, Anti-Thrust

Figure 52. Piston Crown, Cylinder #8

Figure 53. Piston Undercrown, Cylinder #8

4.3.3 Piston Ring Pack

Ring pack measurements show the top (fire), second, and third (oil control) rings for each respective cylinder. No distress was noted for any ring packs removed from the engine, as shown in Figure 54 through Figure 61.

Figure 54. Ring Pack, Cylinder #1

Figure 55. Ring Pack, Cylinder #2

Figure 56. Ring Pack, Cylinder #3

Figure 57. Ring Pack, Cylinder #4

Figure 58. Ring Pack, Cylinder #5

Figure 59. Ring Pack, Cylinder #6

Figure 60. Ring Pack, Cylinder #7

Figure 61. Ring Pack, Cylinder #8

4.3.4 Bearings (Main and Connecting Rod)

Orientation for connecting rod bearings is as follows: upper shell shown left, lower shell shown right, top to bottom cylinders 1 through 8. No shells showed exposed copper. Wear on all shells appears consistent with normal use, as shown in Figure 62.

Figure 62. Connecting Rod Bearings

Orientation for main bearings is as follows: upper shell shown left, lower shell shown right, journals 1 through 5 shown top to bottom (note: main bearing number 5 is at thrust location). As with the connecting rod bearings shown above, none of the main bearings showed any exposed copper. All markings present are consistent with normal use, as shown in Figure 63.

Figure 63. Main (Crankshaft) Bearings

Orientation for crankshaft thrust bearing plates is as follows top to bottom: upper front, lower front, upper rear, lower rear. None of the thrust plates showed excessive wear, as shown in Figure 64.

Figure 64. Crankshaft Thrust Bearing Plates

4.3.5 Valves

Valve orientation for all cylinders are shown as follows: intake left, intake right, exhaust left, exhaust right (Figure 65 through Figure 72). Several of the valve sets show the collection of the light flaked carbon deposits on the intake valves that did not fall off into the port area during storage and handling. These were previously described in the ratings section of the report. In all, the valves removed from the engine were found in good condition.

Figure 65. Intake & Exhaust Valves, Cylinder #1

Figure 66. Intake & Exhaust Valves, Cylinder #2

Figure 67. Intake & Exhaust Valves, Cylinder #3

Figure 68. Intake & Exhaust Valves, Cylinder #4

Figure 69. Intake & Exhaust Valves, Cylinder #5

Figure 70. Intake & Exhaust Valves, Cylinder #6

Figure 71. Intake & Exhaust Valves, Cylinder #7

Figure 72. Intake & Exhaust Valves, Cylinder #8

4.3.6 Valve Cross Heads

Valve cross head orientation is as follows: left column intake, right column exhaust, cylinders 1 through 8 top to bottom. The polished section at the center of the bridge was the area rated for distress, as shown in Figure 73. Although visible wear is noted, it was found to be normal, and below what would be considered critical.

Figure 73. Intake & Exhaust Valve Cross Heads

4.4 SPECIAL INVESTIGATIONS

During the previous dyno testing of the engine prior to tear down, two abnormal conditions were noted by the engines operators during testing. These included an unusual oil pressure and flow fluctuation seen during test measurements made on the dyno, and an oil leak at the engines rear main seal during operation. Special consideration was given to these abnormalities during the engine inspection in an effort to provide some explanation of the root cause, as well as provide a determination if the tested SCPL candidate attributed to these abnormalities.

4.4.1 Lubricating System

After completing the engine dyno testing, TFLRF staff was forwarded a draft report of the TARDEC engine dyno test report to provide background information on the engine testing completed to aid in the inspection of the engine. In this report there was specific notation made of abnormal oil pressure and flow fluctuations that occurred several times during testing. Specifically, a sharp reduction in engine main engine oil galley pressure and a coinciding increase in oil flow rate of the system, that would then be followed at some later time by a sharp increase in oil pressure, and a reduction in overall oil flowrate. Inspection of engine dyno instrumentation and ancillary test stand hardware by TARDEC during dyno testing showed no cause for these abnormal observations, and it was suggested that an internal inspection of the engine components would be required to determine the root cause.

In an effort to understand why these trends occurred, TFLRF staff completed additional inspection of the Cummins 903 lubrication system, focusing on items that either generate or provide control over engine oil flow rate and pressure. A review of the lubricating system present on the engine highlighted three major areas of concern: the engines oil pump assembly, the primary oil pressure/volume regulator at the oil pump, and the engines secondary pressure/volume regulator/bypass valve at the engines oil cooler. No specific notation was made of where in the overall lubricating system that the oil pressure and flow measurements were taken during the TARDEC engine dyno testing, thus no components were ruled out until inspection.

Starting with the oil pump, a visual external inspection was made of the oil pickup tube and oil pump drive gear assembly. No damage or blockage was noted at the oil pick-up, and no debris was present in the oil sump at the time of teardown to suggest supply blockage as a result. The oil pump drive gear showed to be in good visual condition, and the drive system appeared to be in good overall working condition showing smooth rotation and no excessive play. After the initial inspection was completed, the oil pump was then torn down to assess its internal condition. Figure 74 below shows the disassembled oil pump at inspection.

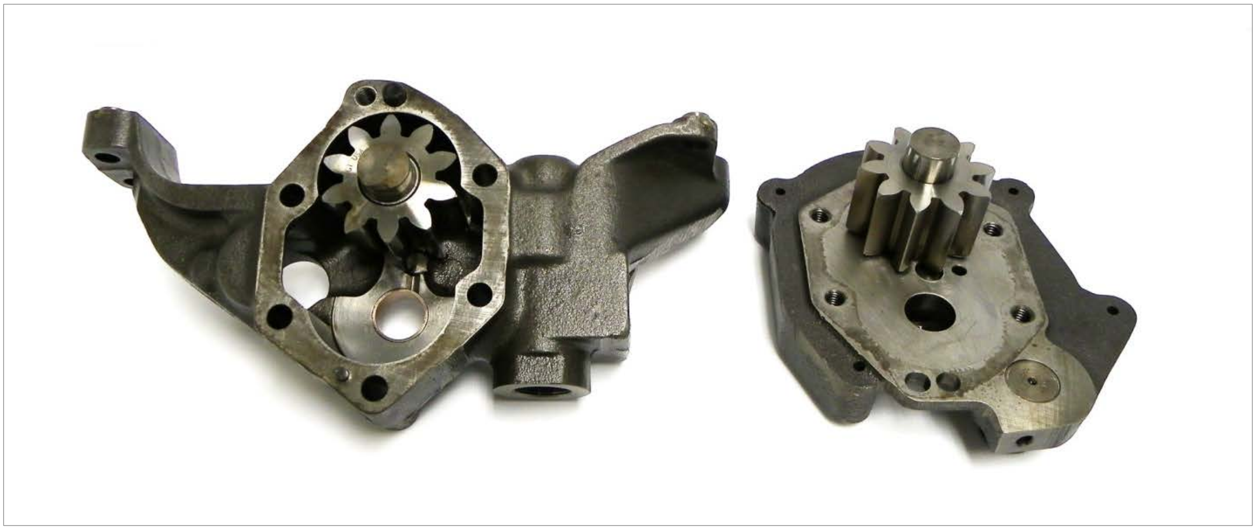

Figure 74. Disassembled Oil Pump Assembly

Figure 75 and Figure 76 on the following page show close up shots of the oil pump cover/drive gear condition. As seen in the photographs, no excessive wear or damage was present on the cover or gear teeth surface. Normal wear of the surface coating on the drive gear teeth was observed, but the overall condition of these components were normal, as expected from typical use.

Figure 75. Oil Pump Cover/Drive Gear

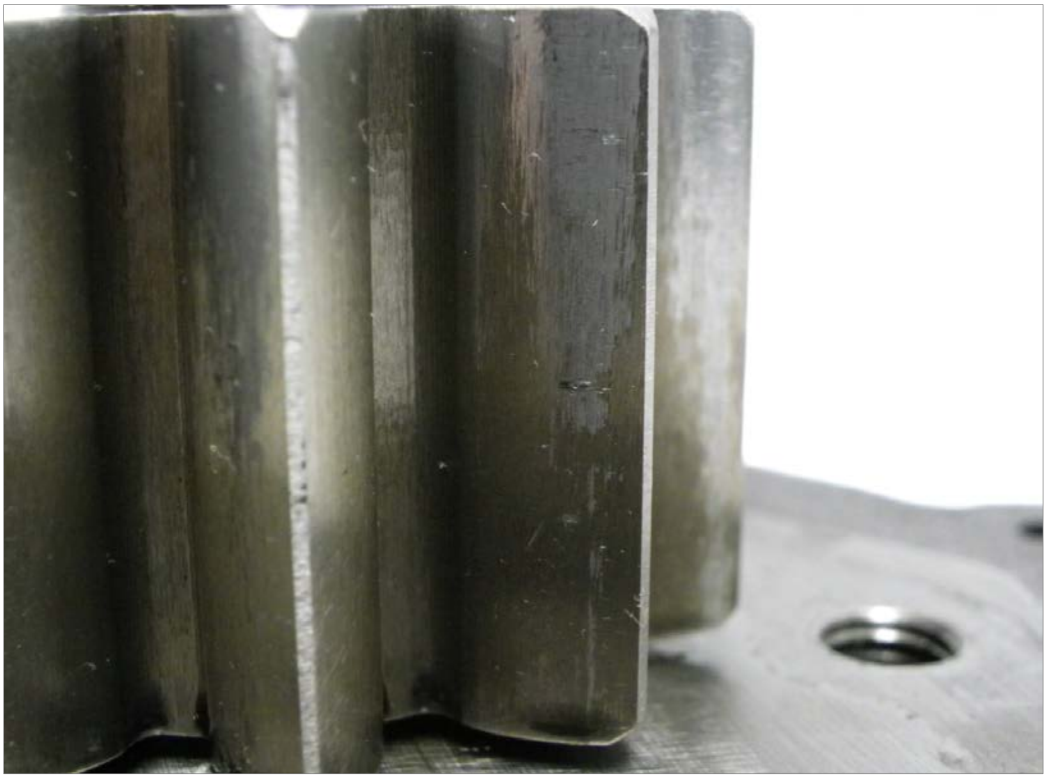

Figure 76. Oil Pump Drive Gear Surface Finish

Figure 77 below shows the remainder of the oil pump housing, and the oil pump idler gear that meshes with the drive gear shown above. Similar surface coating wear was seen on the idler gear complementing that seen on the oil pumps drive gear. The oil pump housing showed no signs of heavy wear, scoring, or polishing of the surface to suggest the oil pump attributed to the abnormal measurements observed during testing.

Figure 77. Oil Pump Housing and Idler Gear

From there, inspection of the primary oil pressure/volume control valve was completed. This valve is physically located in the oil pump housing, and regulates the oil immediately leaving the oil pump before entering any of the engine block drillings/oil passages. Figure 78 below shows the condition of the piston as removed from the pump.

Figure 78. Primary Engine Oil Pressure Relief Piston

As seen in the photo, some wear was noted around the lower circumference of the valve. From previous experience of testing other similar Cummins engines at SwRI, wear in this area was somewhat expected and common. Although present, the valve did not show any signs of sticking upon removal, and failure of this particular valve in a sticking or no movement condition would not substantiate the trends observed by TARDEC. Since the trends observed during testing specifically showed a pressure drop AND flow increase at the same time, that suggested that the fault must have lied later in the lubricating system AFTER the point of measurement, as if the fault occurred prior to the point of measurement, oil pressure and flow would have been expected to have a direct relationship, not inverse as observed (i.e. pressure and flow would increase or decrease together). This knowledge, combined with the physical location of this valve (immediately at the oil pump) ruled out any influence of the primary relief valve as a possible cause, leaving the secondary relief/bypass valve at the oil cooler as the next area for investigation.

Immediately upon investigation of the secondary oil relief/bypass valve, difficulty was noted during its attempted removal from the valve body/bore that it sits in. After working with the assembly, the piston was eventually removed, and surprisingly appeared to be in slightly better condition at the surface than the primary valve seen at the oil pump. This valve can be seen below in Figure 79.

Figure 79. Secondary Oil Pressure Relief/Bypass Piston (Oil Cooler)

After initial inspection, the valve and bore were cleaned and reassembled to further check the fit and movement of the piston within the bore it operates in. A very distinct resistance to movement was occasionally noted when the relief piston was slid up and down in the bore by hand. This resistance to movement was intermittent, and varied as the piston was moved up and down in the bore while also being slightly rotated by hand. A failure or resistance to movement of this particular valve would explain the erratic oil pressure and flow trends observed during testing, assuming oil pressure and flow measurements were taken prior to this valve in the lubricating system. This is likely considering this valves particular location on the engine is at/on the last external piece of hardware of the lubricating system on the engine (i.e. flow and pressure measurements would be expected prior to this point). After removing the valve, inspection of the bore surface was completed to assess condition. When inspected, damage was noted on one of the inner bore surfaces that the piston rides in, and is the likely cause for the intermittent movement of the relief piston. This damage can be seen below in Figure 80 (note, this area of the bore proved difficult to photograph, and the bulk of the bore surface washed out due to lighting. The damage noted can be seen near the very top of the ring on the left hand side of the hole being viewed through). This damage in the bore appears to more consistent with tool damage from previous assembly or disassembly of this component, or could possibly be attributed to foreign object or debris that passed through the oil system and was lodged into the surface by the piston itself. Although the source of this damage is speculatory, TFLRF feels this is the likely cause of the trends noted during operation.

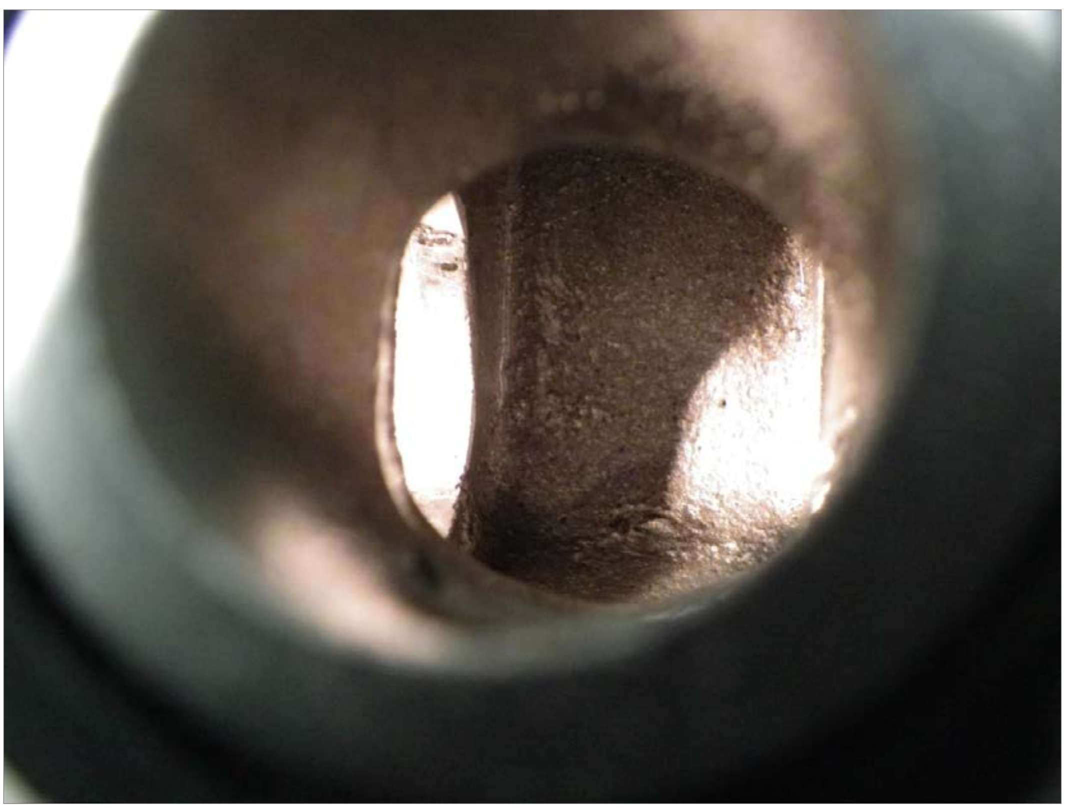

Figure 80. Secondary Oil Pressure Relief/Bypass Valve Bore (Oil Cooler)

For reference, Figure 81 below shows the oil cooler mounting assembly where the secondary relief piston/bypass is located. The location of the photo shown in Figure 80 above was taken through the opening shown directly facing in the photo below. The secondary relief piston/bypass valve is inserted through the bore at the bottom of this housing (note: 90º steel AN fitting considered the top of the housing for frame of reference, secondary relief piston bore opening and movement axis denoted by red arrow).

No other major control components were noted in the lubricating system, with the remainder of the system consisting of drillings for lubricant distribution, and end hardware being lubricated (i.e. engine bearings, rockers, piston squirters, etc).

Figure 81. Oil Cooler Mounting Assembly/Secondary Relief/Bypass Valve Location

4.4.2 Crankshaft Oil Seal

In addition to the oil pressure and flow fluctuations, a significant oil leak was noted by TARDEC at the engines “rear main” seal during dyno testing. TFLRF was asked to pay particular attention to this area upon disassembly to try and indentify the cause of the leak. Upon inspection, it was found that the front crankshaft seal (harmonic balancer end) was the area of the leak as opposed to the rear seal (flywheel end). This was determined by significant accumulation of oil and dirt in this area of the engine. The rear main seal (flywheel end) was clean and showed no evidence of leaking. This discrepancy in terminology is likely just a result of frame of reference differences when discussing the engine, and is compounded by the fact that the Cummins 903 engine sits “backwards” from normally expected when installed into the Bradley Fighting Vehicle (i.e. flywheel end facing front of vehicle). The front crankshaft seal carrier assembly can be seen below in Figure 82.

Figure 82. Crankshaft Seal Housing at Balancer

Close inspection of the seal didn't reveal any obvious defects that would result in oil leaks at this sealing surface. The sealing lip showed uniform wear, with no heavy abrasion or tears present in its surface. The seals lip was also found to be pliable, and would be expected to work as it should. The seal itself also appeared to be installed square and flush in the carrier. Figure 83 shows a close up of the seal lip. Uniform condition was noted around the entire seal circumference.

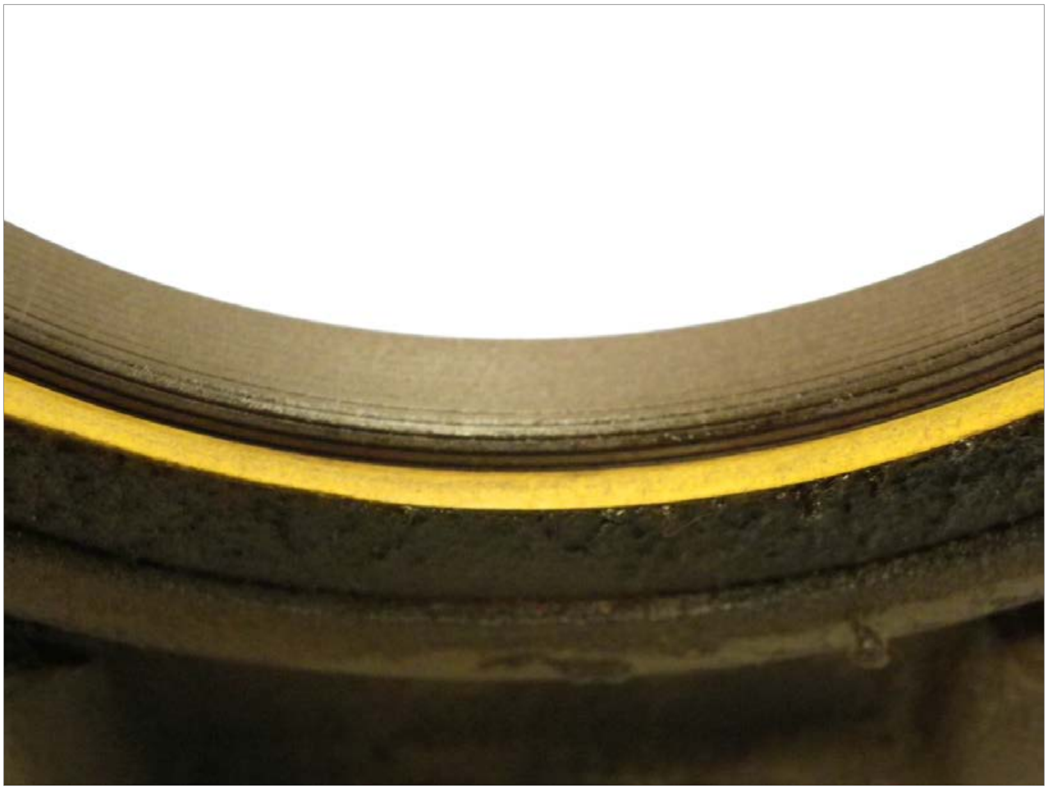

Figure 83. Front Crankshaft Seal Surface Close-up (Balancer End)

In addition, the crankshaft sealing surface was inspected for heavy wear or defects that would contribute to leaks in this area. Although a visible wear pattern was noted where the seals lip rides on the crankshaft surface (noted by the dark line appearing in the surface), there was not significant physical wear to suggest problems. Just past the sealing surface was a heavy accumulation of rust on the surface of the crankshaft, but this area appears to be well outside the area of concern for the seal. This area of the crankshaft is shown in Figure 84.

Figure 84. Crankshaft Front Sealing Surface (Balancer End)

At this time, a definitive cause for the leak in this area was not apparent, although evidence of the leak is obvious upon disassembly. The front seal carrier is bolted to the front of the engine with multiple bolts, but is ultimately located in the x and y direction by the use of one circular dowel pin, and a second semi-circular pin on either side of the seal carrier. It is possible that alignment of the carrier in respect to the engine block (i.e. crankshaft centerline) could be offset and contribute to leaks. Although it would be expected to show wear/evidence on the seal lip surface if the seal was not concentric to the crankshaft due to offset loading. This was not the case. Another potential contributing factor could be not related to the mechanical condition of the seal and sealing surface. Excessive crankcase pressure can also contribute to leaks at sealing interfaces, but data was not apparent for crankcase pressure in the TARDEC draft report, only blow by flow rate. Although there is not enough evidence to determine the true cause of the oil leak, nothing was found that suggested the candidate SCPL as a contributing factor. During its development, the SCPL underwent extensive industry standardized seal compatibility testing, and demonstrated favorable results on par with acceptable commercially available approved lubricants.

5.0 CONCLUSION

In conclusion, it was found that the tested SCPL candidate provided adequate performance in the Cummins VTA-903 engine. The tested candidate provided good deposit control on critical engine components. Results were found to be comparable to those developed using the GEP 6.5L(T) engine during the early phases of the SCPL development program. Overall piston deposit control is acceptable, and testing showed no issues with undesirable deposit build up or stuck or partially stuck rings. Post test engine measurements verified that all components apart from four second ring end gaps were found to comply with the recommended ranges for engine rebuilding. This again suggest good performance and wear protection of the SCPL tested. The four ring end gaps out of specification were found to be a minor non-conformance, and did not raise any real concern of the performance of the SCPL tested. It is the opinion of TFLRF staff that all results gathered support the use of the tested SCPL in this family of engines.

6.0 REFERENCES

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3. ASTM Deposit Rating Manual 20 (Formerly CRC Manual 20), ASTM International, West Conshohocken, PA, www.astm.org.

4. United States (1984). TM 9-2815-219-34: Engine, Diesel: Liquid Cooled V-Type Eight Cylinder Turbocharged Cummins Model VTA-903T, Washington, DC: Headquarters, Department of the Army

APPENDIX A. Compiled Metrology Data – SCPL Evaluation

The following tables include all of the detailed post test metrology results completed on the Cummins VTA-903 engine. The post test liner bore diameter can be seen below in Table A-1.

Table A-1. Post Test Liner Bore Diameter [in]

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	5.5009	5.5003		0.0006
	Middle	5.5008	5.5006	5.5005	0.0002
	Bottom	5.5002	5.4995		0.0007
	Taper	0.0007	0.0011		
2	Top	5.5020	5.5012		0.0008
	Middle	5.5018	5.5014	5.5013	0.0004
	Bottom	5.5007	5.5009		0.0002
	Taper	0.0013	0.0005		
3	Top	5.5019	5.5009		0.0010
	Middle	5.5015	5.5011	5.5011	0.0004
	Bottom	5.5006	5.5006		0.0000
	Taper	0.0013	0.0005		
4	Top	5.5011	5.5002		0.0009
	Middle	5.5007	5.5003	5.5002	0.0004
	Bottom	5.4997	5.4997		0.0000
	Taper	0.0014	0.0006		
5	Top	5.5012	5.5012		0.0000
	Middle	5.5013	5.5008	5.5011	0.0005
	Bottom	5.5008	5.5000		0.0008
	Taper	0.0005	0.0012		
6	Top	5.5007	5.4999		0.0008
	Middle	5.5006	5.5001	5.5005	0.0005
	Bottom	5.5004	5.4995		0.0009
	Taper	0.0003	0.0006		
7	Top	5.5009	5.5009		0.0000
	Middle	5.5010	5.5005	5.5030	0.0005
	Bottom	5.5050	5.4994		0.0056
	Taper	0.0041	0.0015		
8	Top	5.5015	5.5003		0.0012
	Middle	5.5014	5.5005	5.5010	0.0009
	Bottom	5.5005	5.4998		0.0007
	Taper	0.0010	0.0007		

The post test liner bore to piton skirt clearance can be seen below in Table A-2.

Table A-2. Post Test Bore to Skirt Clearance [in]

	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
Post - Test	1	5.5005	5.4881	0.0124
	2	5.5013	5.4884	0.0129
	3	5.5011	5.4880	0.0130
	4	5.5002	5.4883	0.0119
	5	5.5011	5.4882	0.0128
	6	5.5005	5.4883	0.0122
	7	5.5030	5.4882	0.0148
	8	5.5010	5.4881	0.0128

The post test piston ring end gaps can be seen below in Table A-3.

Table A-3. Post Test Piston Ring End Gaps [in]

Cylinder	Ring No.	Before	After	Delta
1	1	N/A	0.020	N/A
	2	N/A	0.022	N/A
	3	N/A	0.021	N/A
2	1	N/A	0.024	N/A
	2	N/A	0.024	N/A
	3	N/A	0.022	N/A
3	1	N/A	0.023	N/A
	2	N/A	0.026	N/A
	3	N/A	0.022	N/A
4	1	N/A	0.021	N/A
	2	N/A	0.021	N/A
	3	N/A	0.020	N/A
5	1	N/A	0.022	N/A
	2	N/A	0.027	N/A
	3	N/A	0.021	N/A
6	1	N/A	0.022	N/A
	2	N/A	0.029	N/A
	3	N/A	0.022	N/A
7	1	N/A	0.020	N/A
	2	N/A	0.022	N/A
	3	N/A	0.021	N/A
8	1	N/A	0.022	N/A
	2	N/A	0.023	N/A
	3	N/A	0.019	N/A

Ring No. 1 max increase	N/A
Ring No. 2 max increase	N/A
Ring No. 3 max increase	N/A

Ring No. 1 avg increase	N/A
Ring No. 2 avg increase	N/A
Ring No. 3 avg increase	N/A

The post piston pin to bore clearance at the connecting rod can be seen below in Table A-4.

Table A-4. Post Test Piston Pin to Bore Clearance in Rod [in]

	Pin Bore in Rod	Pin Diameter	Clearance
1	1.75130	1.74860	0.00270
2	1.75100	1.74870	0.00230
3	1.75115	1.74870	0.00245
4	1.75110	1.74870	0.00240
5	1.75115	1.74870	0.00245
6	1.75110	1.74875	0.00235
7	1.75110	1.74870	0.00240
8	1.75105	1.74870	0.00235

Note: Pin diameter measured in the rod area of the pin

The post piston pin to bore clearance at the piston can be seen below in Table A-5.

Table A-5. Post Test Piston Pin to Bore Clearance in Piston [in]

	Pin Bore in Piston	Pin Diameter	Clearance
1	1.74965	1.74885	0.00080
2	1.74970	1.74895	0.00075
3	1.74970	1.74890	0.00080
4	1.74965	1.74890	0.00075
5	1.74975	1.74890	0.00085
6	1.74970	1.74900	0.00070
7	1.74970	1.74890	0.00080
8	1.74970	1.74890	0.00080

Note: Pin diameter measured in the piston area of the pin

The post test oil control ring to groove clearance can be seen below in Table A-6.

Table A-6. Post Test Oil Control Ring to Groove Clearance [in]

	OC Ring to Groove Clearance	
	Min	Max
1	0.00250	0.00300
2	0.00250	0.00250
3	0.00200	0.00300
4	0.00250	0.00250
5	0.00250	0.00250
6	0.00250	0.00250
7	0.00200	0.00300
8	0.00250	0.00250